HYDROGEOLOGY

OF THE TAKAKA VALLEY

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Frontispiece: The Lower Takaka Valley, with Waitapu Hill to the left and the Pikikiruna Range in the distance

ABSTRACT

The Takaka Valley, in Golden Bay, New Zealand, is renowned as the site of the freshwater spring system known as Waikoropupu Springs, and is also known for its marble karst aquifer. In this project the groundwater resources of the Takaka Valley have been described and evaluated in an integrated analysis, which uses the existing database records supplemented with specific hydrogeological investigations. The intention is to provide information pertinent to the development, management, and long-term protection of the groundwater resources in the region.

The principal aquifer in the Takaka Valley is the karstic Waikoropupu Arthur Marble, referred to as WAM, with primary discharge site at Waikoropupu Springs. The minor karst aquifer is the East Takaka-Motupipi Limestone Aquifer, referred to as ETML. Locally important shallow aquifers are found in the Quaternary gravel deposits which floor the Takaka Valley. These are the Takaka Township Gravel Aquifer and the East Takaka Gravel Aquifer, and are referred to as TTG and ETG.

The complex recharge system of the Waikoropupu Arthur Marble Aquifer is dominated by input via the Takaka river sinks. Other important sources include contributions from tributary stream sinks, the Waingaro river sinks, and allogenic and autogenic diffuse input. The Cobb power scheme, situated on the Takaka River upstream of the major recharge reach, can increase the recharge input into the Waikoropupu Arthur Marble Aquifer with its generation regime, as occurred in 1995-1997.

The primary discharge sites of the Waikoropupu Arthur Marble Aquifer Aquifer are the Waikoropupu Springs. This is a complex arrangement of three subsystems envisaged as a vertical hierarchy, with complex interrelations. The geological and hydraulic controls are complex, as is the water chemistry. The existence of a substantial offshore component of Waikoropupu Arthur Marble Aquifer discharge is refuted. A water balance conducted for the main aquifer shows minimal storage fluctuations. The offshore discharge is not supported by hydrographic analysis, and no affirmative geologic or water chemical information can be offered.

The East Takaka-Motupipi Limestone Aquifer is the minor aquifer in the Takaka Valley and is an important domestic and agricultural supply. The total aquifer extent is subdivided into three sub-aquifers based on interpretation of the structural setting. More detailed hydrogeological subdivision is required before a water balance for the sub-aquifers can be attempted. The recharge system of the entire aquifer is comprised of both allogenic/autogenic, and concentrate/diffuse inputs. Discharge zones are on a small scale in comparison to the Waikoropupu Arthur Marble Aquifer. Water chemistry typifies that of a karstic limestone aquifer.

The Takaka Township and East Takaka Gravel Aquifers are the two Quarternary gravel aquifers of the Takaka Valley studied in this project. They are relied on for domestic and agricultural supply, and both are recharged by diffuse rainfall and river inputs. Water chemical analysis has deemed both supplies suitable for drinking water purposes, but a particular zone in the Takaka Township has been identified with elevated levels of most major constituents.

At the present time, adequate quantitative and qualitative monitoring of the karst and gravel aquifers is not being undertaken. Installation of water level recorders in the gravel aquifers and implementation of further sites in both karst aquifers are recommended. Present qualitative sampling strategies need to be reassessed for all the fore-mentioned aquifers, and specific monitoring in terms of recharge and discharge components requires attention. The preservation and protection of the water resources of the Takaka Catchment, in particular of the Waikoropupu Arthur Marble Aquifer, can be an important focus for the future benefit of all.

TABLE OF CONTENTS

CHAPTER SIX: WATER RESOURCE EVALUATION OF THE TAKAKA RIVER AND THE TAKAKA VALLEY AQUIFER SYSTEM

CHAPTER SEVEN: SUMMARY AND CONCLUSIONS

LIST OF FIGURES

CHAPTER FOUR: HYDROGEOLOGY OF THE LIMESTONE AND GRAVEL AQUIFERS OF EAST TAKAKA AND TAKAKA TOWNSHIP

CHAPTER FIVE: WATER CHEMISTRY AND QUALITY OF THE TAKAKA VALLEY AQUIFER SYSTEM

CHAPTER SIX: WATER RESOURCE EVALUATION OF THE TAKAKA RIVER AND THE TAKAKA VALLEY AQUIFER SYSTEM

LIST OF TABLES

CHAPTER SIX: WATER RESOURCE EVALUATION OF THE TAKAKA RIVER AND THE TAKAKA VALLEY AQUIFER SYSTEM

CHAPTER ONE : INTRODUCTION

1.1 PROJECT BACKGROUND

This Masters of Environmental Science thesis presents a detailed study of the karst and gravel aquifers in the Takaka Catchment, Northwest Nelson, New Zealand (Figure 1.1).

The Takaka Valley is a region of major significance and national importance in New Zealand. Budget restraints on local management teams and on the New Zealand Department of Conservation can leave water catchments such as Takaka without adequate protection and safeguards. This thesis focuses on the two karst aquifers in the catchment area, namely the Waikoropupu Arthur Marble Aquifer, and the East Takaka-Motupipi Limestone Aquifer. Additional investigations concern the gravel aquifers of the Takaka Township and East Takaka areas. The intention is to provide information pertinent to the development, management, and the protection of the groundwater and surface water resources.

Past research work conducted on the Takaka Valley is developed and extended, and the existing data and information is evaluated. Existing methodologies and methods of control are described and critically evaluated, and suggested improvements are outlined. It is intended that the results be used in the implementation of the Takaka Water Management Plan.

The functioning of the aquifer systems are re-examined, and in some cases previous theories are rejected. New models are proposed which take into account all the parameters observed, and which are better representations of these complex hydrological systems.

Figure 1.1. Location of the Takaka Catchment, Northwest Nelson, New Zealand. Taken from NZMS 265, Sheet 2 South Island, 1:1 000 000 (Map reproduced by permission of Land Information NZ: Crown Copyright Reserved)

1.2 THESIS OBJECTIVES

This thesis aims to comprehensively review all relevant hydrological, hydrogeological, and geologic information for the Takaka Catchment, and to utilise the extensive database which exists for both the surface and groundwater resources in the valley.

The primary objective of this thesis is to evaluate the groundwater resources of the Takaka Valley aquifer system. Secondary objectives are:

- to investigate and quantify the recharge processes and the discharge zones associated with the main karst aquifer in the catchment,
- to assess the hydrogeological characteristics of the minor aquifers in the Takaka Valley,
- to provide baseline assessment of the water quality of surface and groundwater,
- to derive an updated water balance model for the main aquifer, and
- to make a preliminary assessment of the effects of the Cobb power station on the upper Takaka River regime and the main aquifer recharge system.

The study area consists of a 928 km^2 north-south trending catchment located approximately 100 km north-west of Nelson. For the purposes of this thesis it is divided into the following subcatchments : Upper Takaka (including Cobb), Waingaro, Anatoki, Waitui, Central Takaka Valley, Lower Takaka Valley, and Motupipi (Figure 1.2).

This thesis does not provide in-depth analysis of hydraulic characteristics of aquifers: data limitations have precluded assessment. Instead it offers an overview of the Takaka Valley aquifer system, concentrating on the processes and functioning of the major and minor aquifers. As such it will be useful for the management of both surface and groundwater resources.

1.3 PREVIOUS WORK

The Takaka Catchment has been the subject of numerous geological and hydrogeological studies and investigations. Important references, are listed below. Numerous additional reports and discussion documents are available, covering

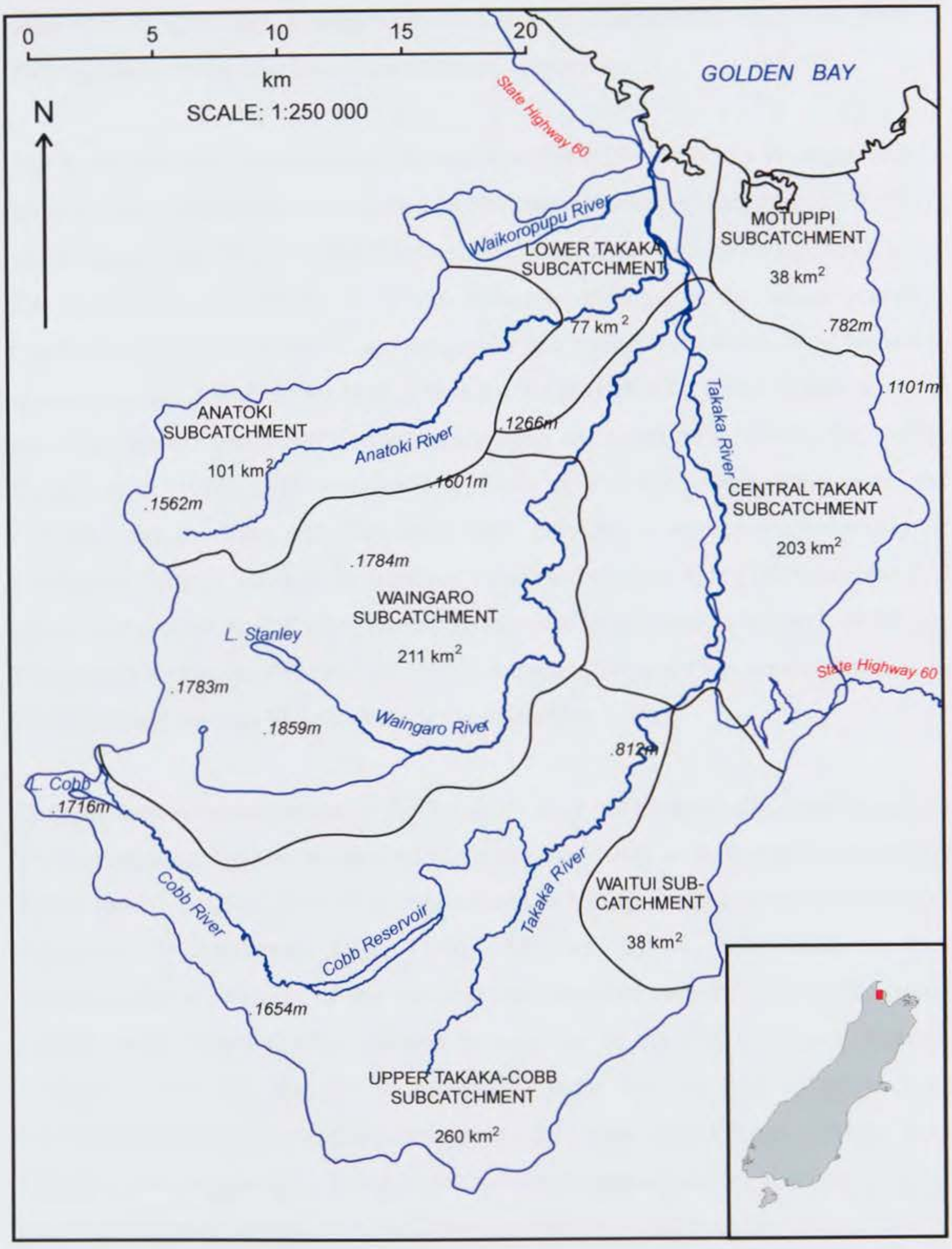


Figure 1.2. Hydrological boundaries and areas of subcatchments adopted in this thesis

areas such as hydrology, hydrogeology, geophysical interpretation, and water quality. They will be referred to in later chapters where appropriate.

The geology of the Takaka Valley was described by Bell (1908) and Wellman (1945), and was later mapped (in conjunction with Northwest Nelson) by Grindley (1971, 1981) and Bishop (1968, 1971). While Grindley's mapping of the Takaka Valley is still valid, his interpretation, especially of Lower Paleozoic geology, is no longer accepted. Current interpretation of Paleozoic stratigraphy and structure for North-West Nelson is given in Cooper (1989), Roser et al (1996) and Jongens (1997). Leask (1980) provided the most detailed analysis of Tertiary stratigraphy and structure in Golden Bay, while Nathan et al (1986) gave a regional synthesis of the West Coast Cretaceous and Cenozoic strata. King and Thrasher (1996) provided a more recent summary of Cretaceous-Tertiary basins in the southern Taranaki complex. Judd (1989) incorporated all existing onshore and offshore seismic geophysical information in his study of the late Cenozoic deformation of Golden Bay. Only limited information has been collated about the Quaternary geology in the Takaka Valley (Grindley 1971).

Hydrogeological investigations in the Takaka Valley have historically concentrated on Waikoropupu Springs, on the geological features proximal to these, and on the major Arthur Marble aquifer. Very early observations and interpretations were given in Park (1890) and in Henderson (1928, 1948). Michaelis (1974, 1976) made the first comprehensive assessment of the physical and chemical properties of Waikoropupu Springs, while Rapier (1975) provided an overview of the hydrogeological features. Williams (1977) was the first to prove (via pulse train analysis techniques) the connection between Waikoropupu Springs and the Upper Takaka River recharge zone. This had been suggested by many of the writers mentioned above. Isotopic analyses indicated that water issuing from Waikoropupu Springs had a spectrum of ages (3 to 10 years), and averaged 8 years (Stewart and Downes 1982).

The recognition of three important water bearing formations in the Takaka Valley, namely Arthur Marble, Takaka Limestone and Quaternary gravels, led to wider hydrogeological study requirements. Stewart and Williams (1981) used stable isotope analysis to describe recharge of the three aquifers. Unfortunately the analysis claimed one bore to be in marble, but it was later confirmed to encounter limestone (Mueller 1987). There was, however, valid analysis of the Quaternary gravels In 1987 Mueller was commissioned by the Nelson Marlborough Regional Council (now the Tasman District Council) to investigate the Takaka Valley aquifer system. While Mueller's work (1987, 1991, 1992) provided the most comprehensive assessment of the hydrogeology of the Takaka Valley, some of the interpretations are based on unsubstantiated estimates.

1.4 REGIONAL GEOLOGICAL SETTING

The Takaka Catchment lies within the Takaka Terrane, a structurally complex and dismembered belt of Lower Paleozoic rocks (Cooper 1989). Previous division of the early Paleozoic rocks, based on Grindleys' interpretation (1971, 1981), had divided the area into Eastern and Central Sedimentary Belts. The current interpretation has the Anatoki Thrust in Northwest Nelson marking the boundary between the Paleozoic Takaka Terrane (eastern) and Buller Terrane (western) (Jongens 1997, Cooper 1989). Division is based on New Zealand Terrane classification. The Takaka Terrane contains a wide range of lithofacies and rocktypes, and spans an age range of hundreds of millions of years, from Middle Cambrian to Devonian (Roser et al 1996). Of primary interest in this thesis is the Ordovician Arthur Marble (Cooper 1989). Details of Paleozoic stratigraphy are shown in Figure 1.3, and the geological time periods are given in Appendix A-I.

Late Cretaceous-earliest Tertiary marked the beginning of deposition of the non-marine Brunner Coal Measures across northern and western Northwest Nelson (Cooper 1984, Leask 1980, Wellman 1945). In the Takaka Valley coal measures are locally referred to as Motupipi Coal Measures (Grindley 1971), and are of Eocene age. Paleocurrent directions and facies relationships indicate that the depositional basin was originally narrow and north trending, and resembled the shape of the present day Takaka Valley (Nathan et al 1986, Leask 1980). Between deposition of the oldest and youngest coal measures (i.e. between Late Cretaceous-late Eocene), the Northwest Nelson peneplain formed, approximately 60 million years ago. The peneplain, first recognised by Cotton (1916), represents a significant period of subaerial erosion. It was during this time that primary karsification of the Arthur Marble occurred. The peneplain surface has been

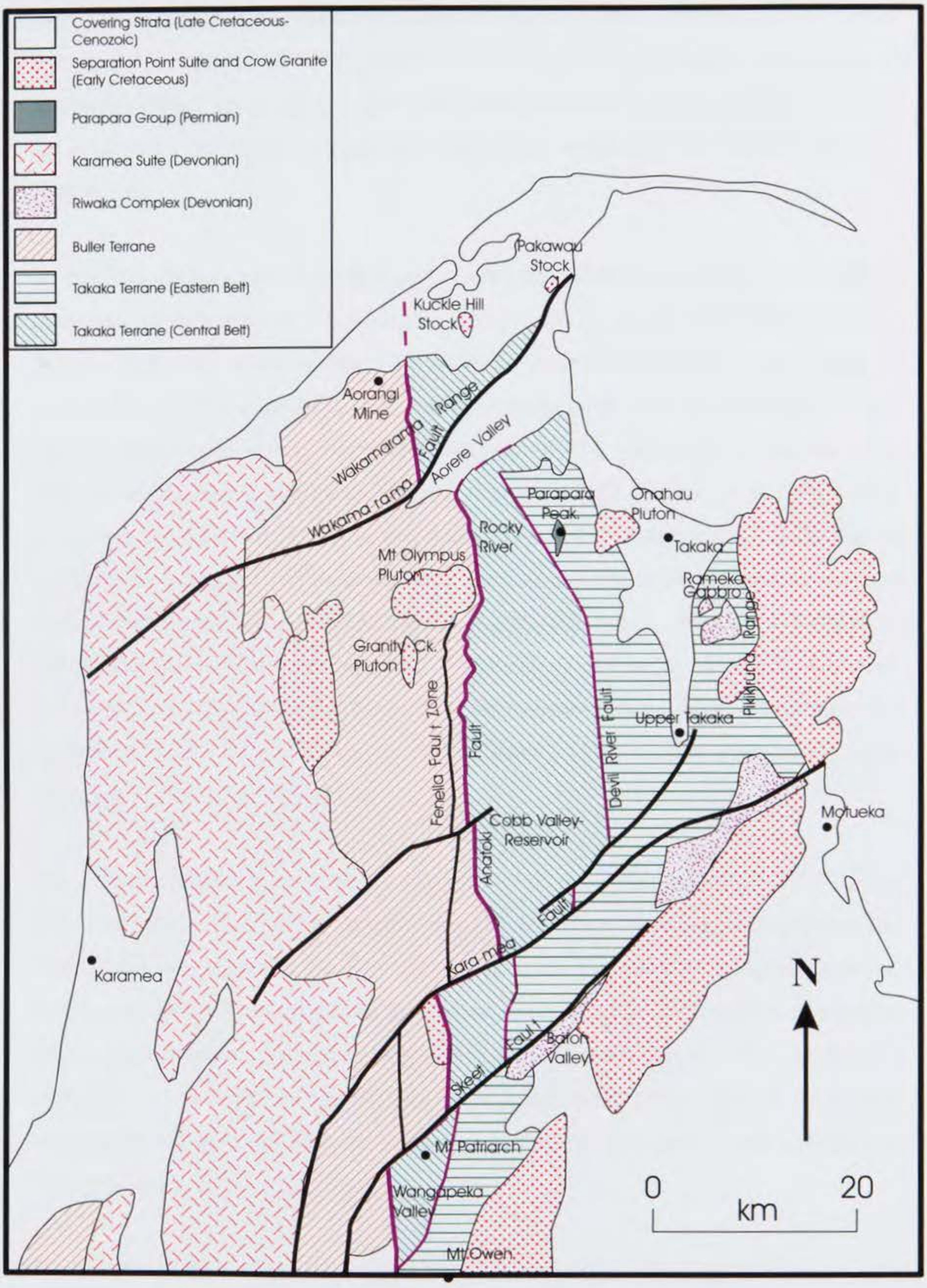


Figure 1.3. Generalised geology of Northwest Nelson (After Jongens, 1997; adapted from Cooper and Tulloch, 1992, and Muir *et al*, 1996b)

used as a reference from which to measure later deformation (Wellman 1939). By the Eocene the peneplain had disintegrated in the Takaka Valley (Mueller 1991). Much of Northwest Nelson remained emergent until Mid-Oligocene. A relatively flat surface of the resurrected peneplain can still be clearly seen today from the Takaka Hill road (Figure 1.4).

By the Mid Tertiary there had been widespread deposition of limestone and carbonate sandstone in the Northwest Nelson region (Cooper 1984). Leask (1980) identified three factors conducive to deposition. These were the relative tectonic quiescence, the completion of a New Zealand wide marine transgression, and the funneling of high energy nutrient-laden currents on to New Zealand. By the Waitakian virtually the entire West Coast (including Northwest Nelson) was submerged (Nathan et al 1986). This resulted in deposition of Takaka Limestone of variable thicknesses in the Takaka region. A change in pattern of sedimentation took place at the end of the Oligocene; renewed tectonic activity led to a regional change from sediments rich in carbonate to terrigenous clastic sediments (Nathan et al 1986). Deposition of marine Tarakohe Mudstone continued until the end of the Tertiary. The youngest marine beds, sandstones, and mudstones in the Takaka Valley are approximately 10-15 million years old (Cooper 1984, Leask 1980, Grindley 1971).

Major structural deformation began post Miocene (after the deposition of Tarakohe Mudstone) and resulted in the development of fault scarps along the Wakamarama and Pikikiruna Faults (Figure 1.3). This activity led to the formation of faulted depressions. Reactivation of the karst systems in the Pleistocene resulted in the formation of complex subterranean drainage systems. The present day Takaka and Aorere Valleys provide a record in part or in full of the Tertiary sequence (Cooper 1984). Details of Tertiary stratigraphy are given in Chapter Two, and geological time periods are presented in Appendix A-I

The Takaka Valley contains both gravel and karst aquifers. The rock units of specific hydrogeological interest are Ordovician Arthur Marble (the primary karst aquifer in the study area), Oligocene Takaka Limestone (the secondary karst aquifer in the study area), and Quaternary gravel deposits (additional localised gravel aquifers in the study area).

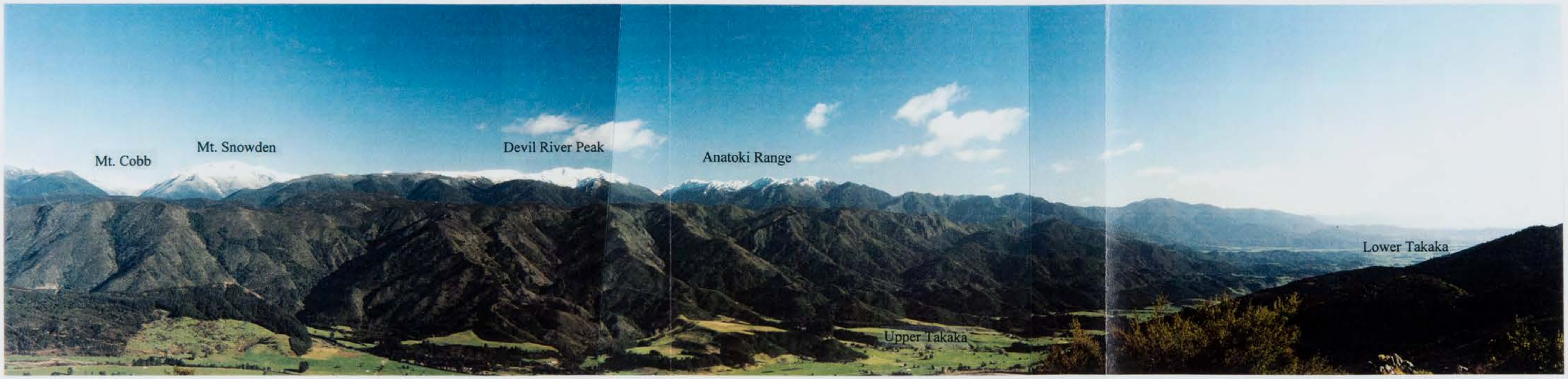


Figure 1.4. View of the Northwest Nelson peneplain from Takaka Hill (Harwoods Lookout)

1.5 KARST GEOMORPHOLOGY OF THE TAKAKA CATCHMENT

Karst is defined as a type of geologic terrane underlain by carbonate rocks, where significant solution of rock has occurred due to flowing groundwater (Fetter 1994). Depressions, disrupted surface drainage, caves, and underground drainage systems are characteristic features of karst regions. The degree of development of these features varies greatly from one area to another (White 1988).

The Takaka Catchment possesses a number of karst landforms in Arthur Marble which have national and international significance. These include Waikoropupu Springs, Harwoods Hole, and the Takaka Hill karst plateau.

Waikoropupu Springs is an internationally significant karst artesian spring, the largest in the southern hemisphere (Worthy 1990) and the 24th largest in the world (Ford and Williams 1989). The springs are the primary discharge zone for the major karstic aquifer underlying the Takaka Valley. Because of the fragile nature of their environment, and their ecological significance (Michaelis 1974, 1976, 1977), Waikoropupu Springs is managed by the Department of Conservation and is designated as a scenic reserve.

Harwoods Hole is a 176 m freefall tomo (pothole), and is the deepest open shaft in New Zealand. The present drainage system resurges in Gorge Creek; the former water course drained via Harwoods Hole to the Starlight-Cave system. The vertical separation between the active and abandoned waterways is approximately 145 m (Williams 1987). Harwoods Hole and part of the Canaan Downs are incorporated in the Abel Tasman National Park.

The Takaka Hill karst plateau (at elevation 600-800 m) represents an area bounded by the Kairuru Quarry and the summit of the Canaan Road. The area is an example of inactive polygonal karst displaying low relief sinkholes, which are still vegetated (Figure 1.5). Karst landforms of the Takaka Valley studied in this thesis are described in greater detail in later chapters.

Figure 1.5. Karst terrain of Takaka Hill

1.6 HYDROLOGICAL SETTING

1.6.1 River systems

The largest river in the study area is the Takaka River, which has a total catchment of 890 km^2. Its headwaters drain from above 1000 m in the Arthur Ranges through gorge country for approximately 11 km, before meeting the first of four important western tributaries, namely the Cobb River (Figure 1.2). The Cobb River input is modified by hydroelectric development. The flow component which joins the Takaka River is comprised of natural input, spillway discharge from the Cobb dam, and artificial generation releases from the Cobb power station.

The second important Western tributary, the Waingaro River, meets the Takaka Valley 30 km downstream of the Cobb-Takaka confluence in the central valley, at Paynes Ford (N26 940359). The Waingaro drains from the Douglas and Snowden Ranges, at elevations in excess of 1500 m, and has a total catchment area of 211 km^2 (Figure 1.2). It is a major river in its own right, with important tributaries of note including the Stanley and Devil Rivers.

The Anatoki River is the third important western tributary of the Takaka River and drains a catchment of 101 km^2, with its head waters in the Anatoki Range. For some of its length the Anatoki River is confined to deep narrow valleys, and has only minor tributaries (Figure 1.2). The Anatoki River-Takaka River confluence is 500 m west of the southern end of Takaka township (N26 931385).

The Waikoropupu River is the final western tributary, meeting the Takaka River at N25 926409. It is a predominantly spring fed river, with additional overland flow derived from its headwaters in the Walker Ridge-Parapara Ridge area. The Takaka River then discharges into Golden Bay between Waitapu and Rangihaeata (N25 932431 - N25 925439).

Important Eastern Tributaries of the Takaka River include Waitui Stream, Gorge Creek and Rameka Creek. The latter two drain from the Pikikiruna Ranges, while the headwaters of the Waitui Stream are in the Arthur Range at the southern extremity of the field area.

In the Takaka Catchment the complex interaction of river/aquifer and the role of karstic geology are most apparent during low flow periods. The Takaka and Waingaro Rivers both cross major loss zones, as do the majority of the minor contributing streams and creeks that drain the foothills of the eastern and western ranges. The Takaka River runs dry for a section downstream of Lindsays Bridge (N26 952260) to Spring Brook (N26 933312) for approximately 100 days of the year. The existence and quantification of swallets, loss zones, and sinking streams will be discussed in Chapter Three. Summary statistics for low flows, as well as for flood flows in the major rivers in the Takaka Catchment, are given in Appendix C.

1.6.2 Springs systems

Waikoropupu Springs, commonly referred to as Pupu Springs, is the major karstic spring system in the Takaka Catchment and the largest spring in New Zealand (Figure 1.6). The springs are located within the Waikoropupu Valley 3 km west of the Takaka township and approximately 4 km south from the coast (Figure 1.7). Davies-Colley and Smith (1995) recently recorded clarity and optical properties of the spring water, and declared it to be the clearest water in the world. The total spring system covers an area of 4.5 km^2 and incorporates 16 vents, which can be subdivided into three sub-systems. These are named Main Springs, Dancing Sands, and Fish Creek Springs (Mueller 1987, 1992). Characteristics of note include clear tidal oscillations (correlated with the twice daily Golden Bay tides), and a constant temperature of 11.7° (Michaelis 1974, 1976).

Numerous additional intermittent and ephemeral springs exist in the Takaka Catchment, those of principal interest being depicted in Figure 1.7. Spittals Springs and Spring Brook discharge from Ordovician Arthur Marble, whilst Motupipi Springs and East Takaka Springs discharge from Takaka Limestone. All these springs are recharged via a combination of rainfall infiltration and groundwater seepage. The Spittals Springs

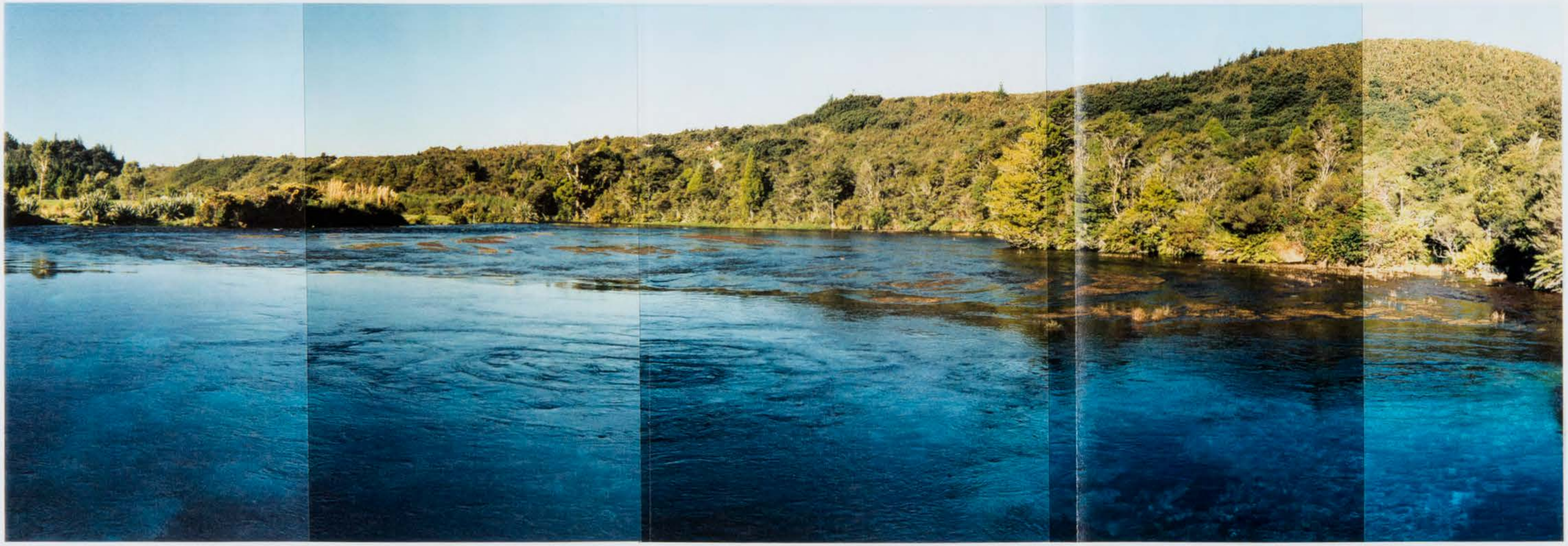


Figure 1.6. Main Springs vent, Waikoropupu Springs.

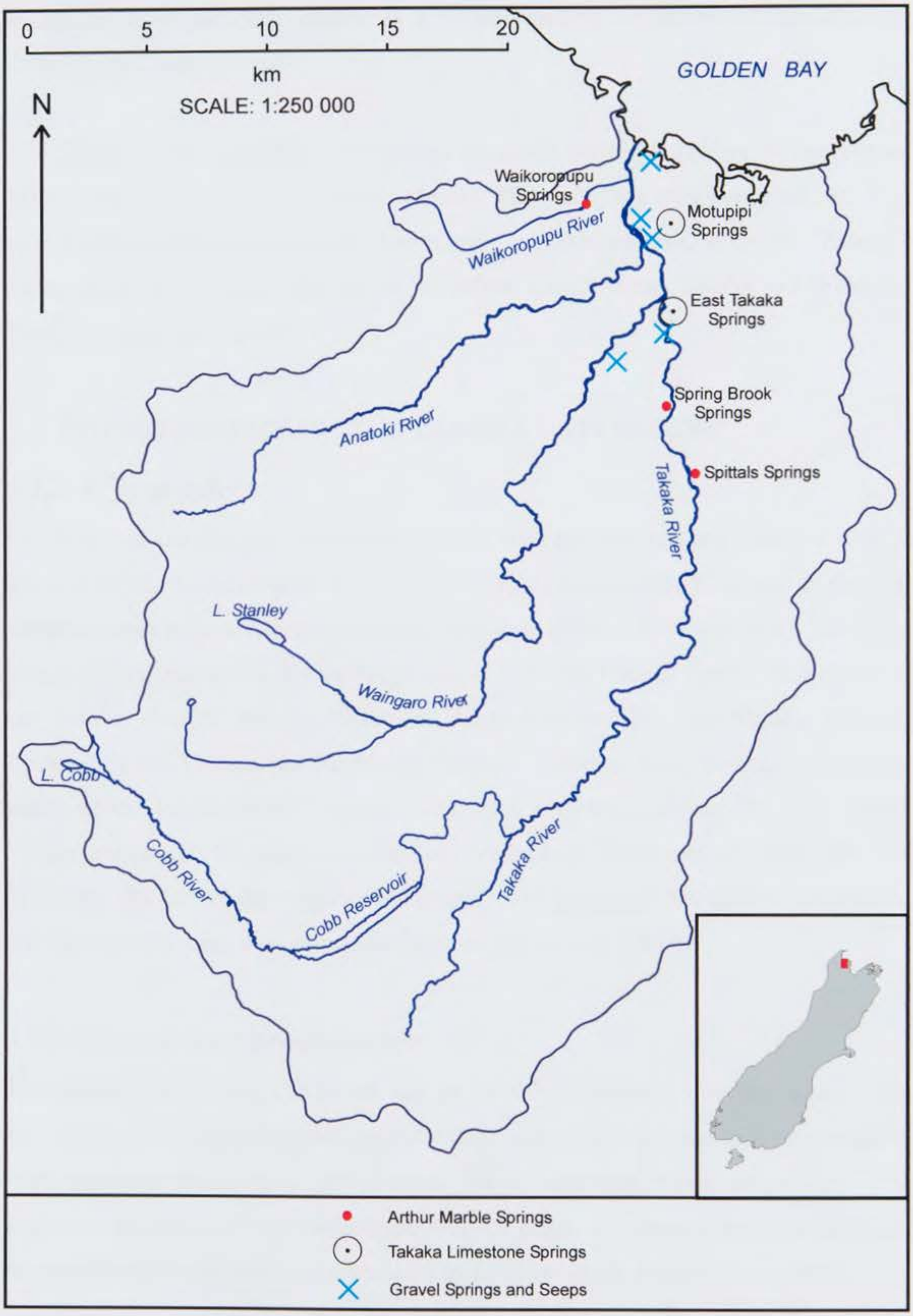


Figure 1.7. Location of marble, limestone and gravel springs in the Takaka Catchment

resurgence is of particular interest as it is connected to the Harwoods hole-Starlight Cave-Gorge Creek system.

In addition to the carbonate rock springs discussed above, a number of intermittent Quaternary gravel seeps exist in the catchment They only flow after heavy rain and high river flows and tend to be located in proximity to rivers, streams, or creeks. Example locations of known seeps that act as "overflow seeps" to the Takaka and Waingaro Rivers are shown in Figure 1.7.

1.7 PHYSIOGRAPHY OF THE TAKAKA CATCHMENT

1.7.1 Topography

The terrain of the Takaka Catchment is varied, with altitudes ranging from sea level to the peak of Mt. Snowden at 1859 m (M26 766190). Approximately 287 km^2 of the total catchment area is mountainous terrain (at more than 1000 m above sea level). Mountain ranges of note include the Arthur Range, the Anatoki and Haupiri Ranges (sub-ranges of the Tasman Range), and the Pikikiruna Range (Figure 1.8). The Takaka valley is bounded by the Tasman and Pikikiruna Ranges. The river flats, terraces, and coastal plains of the Takaka Valley, together with small contributions from the deep narrow valleys within the Waingaro and Anatoki Valleys (at elevations less than 500 m), constitute 281 km^2 of the total catchment area. The remaining 359 km^2 is intermediate hill and alpine terrain, with elevations between 500 m and 1000 m.

1.7.2 Climate and precipitation

Climatically the Takaka Catchment can be broadly subdivided into two zones. The cool-wet coastal and cool-humid central valley sections are characterised by average to high sunshine hours, long dry summer spells, and rare frosts in winter. The mountainous terrain of the eastern and western ranges experience more variable and severe climatic conditions, and commonly incur snowfalls in winter (Bruce 1987).

Figure 1.8. Topography of the Takaka Catchment. Taken from NZMS 262, Sheet 9 Nelson, 1:250 000 (Map reproduced by permission of Land Information NZ: Crown copyright Reserved)

Rainfall varies both seasonally and areally. The mean annual rainfall ranges from a maximum of 5140 mm at the headwaters of the Anatoki River (Caesars Knob M26 759333) to a minimum of 1542 mm at Tarakohe (N25 016425) (Appendix D). The variable areal precipitation distribution is clearly shown in the catchment isohyetal map (Figure 1.9). Major contributing factors to precipitation variability are the altitudinal variation within the catchment, and the orographic effect that prevails in the western ranges.

Precipitation associated with northerly, nor-easterly, and westerly storms primarily affects the Central Takaka Valley, the Western Ranges, and the Eastern Ranges respectively. As a result, fairly localised rainfall conditions exist: specific rainfall events affect certain areas more than others, and in some instances affect only certain subcatchments.

Rainfall is well distributed throughout the year (Figure 1.10) with above average precipitation levels in the months of July, August, and September. It is common to have extended periods (weeks) of nil precipitation in the valley during the summer months from December to March.

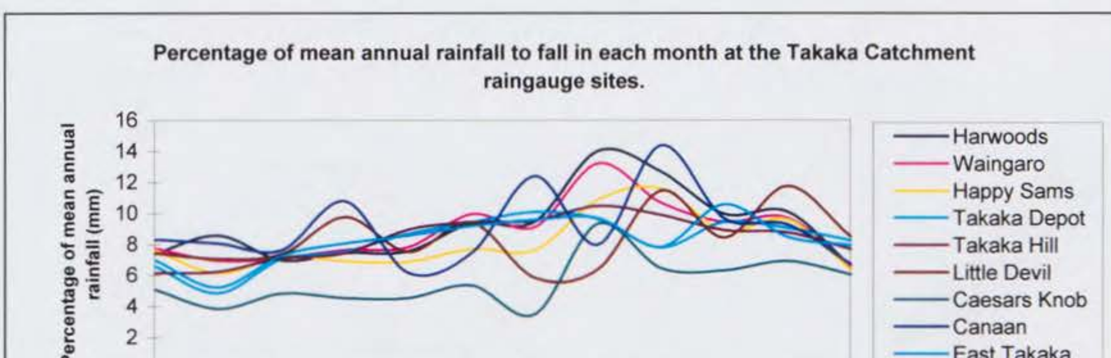


Figure 1.10 Seasonal rainfall patterns in the Takaka Catchment. Data is derived from Tasman District Council. Data periods vary from 3 years to 15 years.

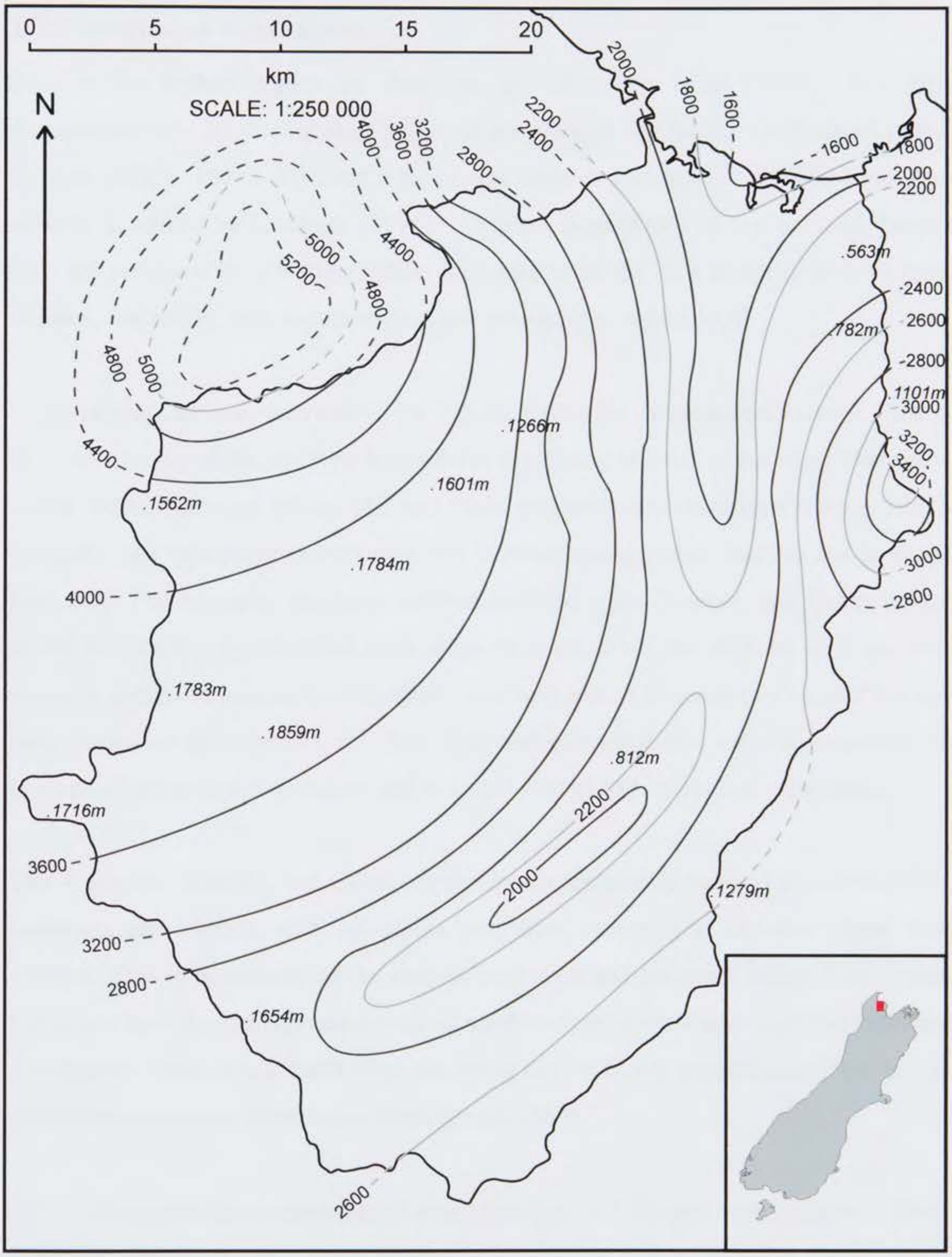


Figure 1.9. Areal isohyetal rainfall distribution for the Takaka Catchment.
Contour values in mm, spot heights in metres.

1.7.3 Soils and vegetation

Soils of the Nelson region are described by Chittenden *et al* (1966). Soil type distribution maps for the Takaka Catchment are given in the Takaka Catchment Control Scheme (TCCS, 1984). Updated regional soil maps at a scale of 1:1000000 have been recently produced by Landcare (1996). Detailed descriptions of the lowland Takaka soils are presented in O'Byrne (1983). Distribution of the soils in the river flats, fans, terraces, and rolling hills is summarised and presented in Appendix E.

Soil type plays an important role in the Takaka Valley for two principal reasons. Firstly, an understanding of the soil type is helpful in explaining features of the water chemistry, which include nutrient status, pH, and trace element concentrations (Roberts 1993). Secondly, soil type plays an important role in determining present landuse and potential land use. For example, the more nutrient-enriched soils (Tasman and Karamea) are suited to intensive farming of a wide range of crops, while the Redzina soils are well suited to improved pasture development. Soil type and its interaction with land use has been presented in Appendix E. Soil type and characteristics are also important in analysis of groundwater recharge, and in assessment of soil infiltration capacities.

The Waingaro, Anatoki, and Cobb subcatchments are largely covered in native beech, podocarp, and tussock, with sub-alpine vegetation occurring at altitudes higher than 1300 m. This is in contrast to the eastern catchment and the main valley floor, which have been heavily modified and consist of scrubland, or reverted and modified grassland and pasture. Only minor tracts of exotic forest can be found, predominately situated in the Waikoropupu and Uruwhenua areas (Bruce 1987).

Table 1.1 presents the percentages of vegetation type and the area each occupies. These figures are derived from a map of vegetation distribution first presented in 1984 (Takaka Catchment Control Scheme Report 1984). They are considered valid and representative, as there has been little change in vegetation in the Takaka region over the last 15 years (pers. comm. Burton 1997).

Table 1.1 Vegetation type, total area (in km^2), and percentage contribution for the Takaka Valley

Vegetation type	Total area (km^2)	Percentage contribution
Indigenous vegetation, alpine tussock and scrub	680	73 %
Grassland	126	14 %
Scrub and reverted land	113	12 %
Exotic forest	8	0.9%
Cropland	1	0.1 %

1.7.4 Land use

Development of land within the Takaka Catchment is primarily concentrated in the Main Takaka, Waingaro, Anatoki, and Waikoropupu Valleys. Major land uses include agriculture, horticulture, and small scale forestry development.

Agriculture is the principal landuse, and mainly involves dairy farming. Beef production, sheep farming, and deer farming have much less significance. Important farming areas are situated along the lower reaches of the Takaka, Waingaro and Anatoki Rivers and at East Takaka and Motupipi.

The amount of land used for horticulture has fluctuated in the past 20 years. Figures for the total area planted in kiwifruit rose from 30 hectares in 1984 to approximately 200 hectares in 1987 (Bruce 1987). This figure has subsequently decreased in the last 10 years, due to the removal of a number of large orchard blocks and their conversion to pasture land. Horticultural practices are invariably situated where the better quality soils occur and where frosts are less frequent and severe, i.e. in the Lower Takaka Valley.

Other minor land uses in the Takaka catchment include exotic forestry, viticulture, and assorted cottage industries.

1.7.5 Water use

Surface water and groundwater in the area is used for domestic supply and irrigation. Other activities which have a direct affect upon the water resource include hydroelectric development and salmon farming.

The major hydroelectric scheme, situated in the Upper Takaka subcatchment, dams the natural Cobb River flow in the Cobb reservoir. It has a maximum generation capacity of 32 MW. Downstream hydrological effects of the Cobb generation releases are discussed in Chapter Six. Other small scale hydroelectric schemes include the Pupu scheme, located in the Waikoropupu valley, and the Ellis Creek scheme, located in the eastern ranges. Future development of small scale hydroelectric schemes is proposed for the Rameka Catchment.

The Southern Ocean Salmon Farm (formerly Bubbling Springs Salmon Farm) diverts water from the Springs River before it reaches the Waikoropupu River. This farm is a principal water user of the Ordovician Arthur Marble aquifer system. There is also the possibility that commercial bottling of spring water may develop in the future. The Tasman District Council has set an interim limit of 0.5 m^3s^{-1} for total abstractions from the recharge zone for the Waikoropupu Springs system (Fenemor 1991).

Domestic and irrigation water use is derived from surface flow, the Takaka Limestone aquifer, or the Quaternary gravel aquifers. Limited use is made of the Arthur Marble aquifer. In most areas of the Takaka Valley conjunctive water use is in place. Demand for water in certain regions, e.g. in East Takaka, Motupipi, Clifton and Tarakohe, is such that surface flow is unable to meet requirements. In some cases, householders and farmers use bores up to 100 m deep for water supply. A total of 48 surface and 27 ground water permits have been granted within the Takaka Valley and surrounds.

1.8 TAKAKA CATCHMENT MONITORING NETWORK AND EXISTING DATABASE

1.8.1 Climate monitoring network

Basic observations of ambient temperature, wind direction, and cloud cover recorded at the Cobb power station and at Cobb dam are available for the Takaka Catchment. There are no evapotranspiration stations in the catchment, the closest site being situated over the Takaka Hill at Riwaka (N26 034172).

1.8.2 Rainfall monitoring network

The Takaka Catchment and surrounds has a working network of six automatic telemetry accessible rainfall sites. These are situated at Harwoods, Kotinga, Waingaro at Hanging Rock, Anatoki at Happy Sams, Little Devil at Tarn, and Anatoki at Caesars Knob. The latter two sites are at altitudes above 1300m. Records for an additional seven open rainfall sites and nine closed sites exist. Full details and locality information for all sites are given in Appendix B and Figure 1.11.

1.8.3 River monitoring network

Flow data is available for eight permanent flow recorders in the Takaka Catchment. The sites used primarily in this thesis include Takaka River at Harwoods, Takaka River at Kotinga, Waingaro River at Hanging Rock, and Anatoki River at Happy Sams. Other flow sites used to a lesser extent are Cobb at Trilobite, Rameka at Pages Ford, and Elm Grove at Springs River. Additional flow data is available for Cobb reservoir spill discharges and Cobb power station machine discharges. The details of each site, including the primary reason for its existence, are given in Appendix B. Locations are shown in Figure 1.1. In addition to continuous recordings, discrete flow records are available for selected flow gauging runs performed in the Takaka Catchment.

This thesis primarily uses available gauging data to track flow losses downstream. These matters are dealt with in greater detail in subsequent chapters Three and Four. All available gauging data (other than that collected for the purposes of rating curves) is presented in Appendix C-II.

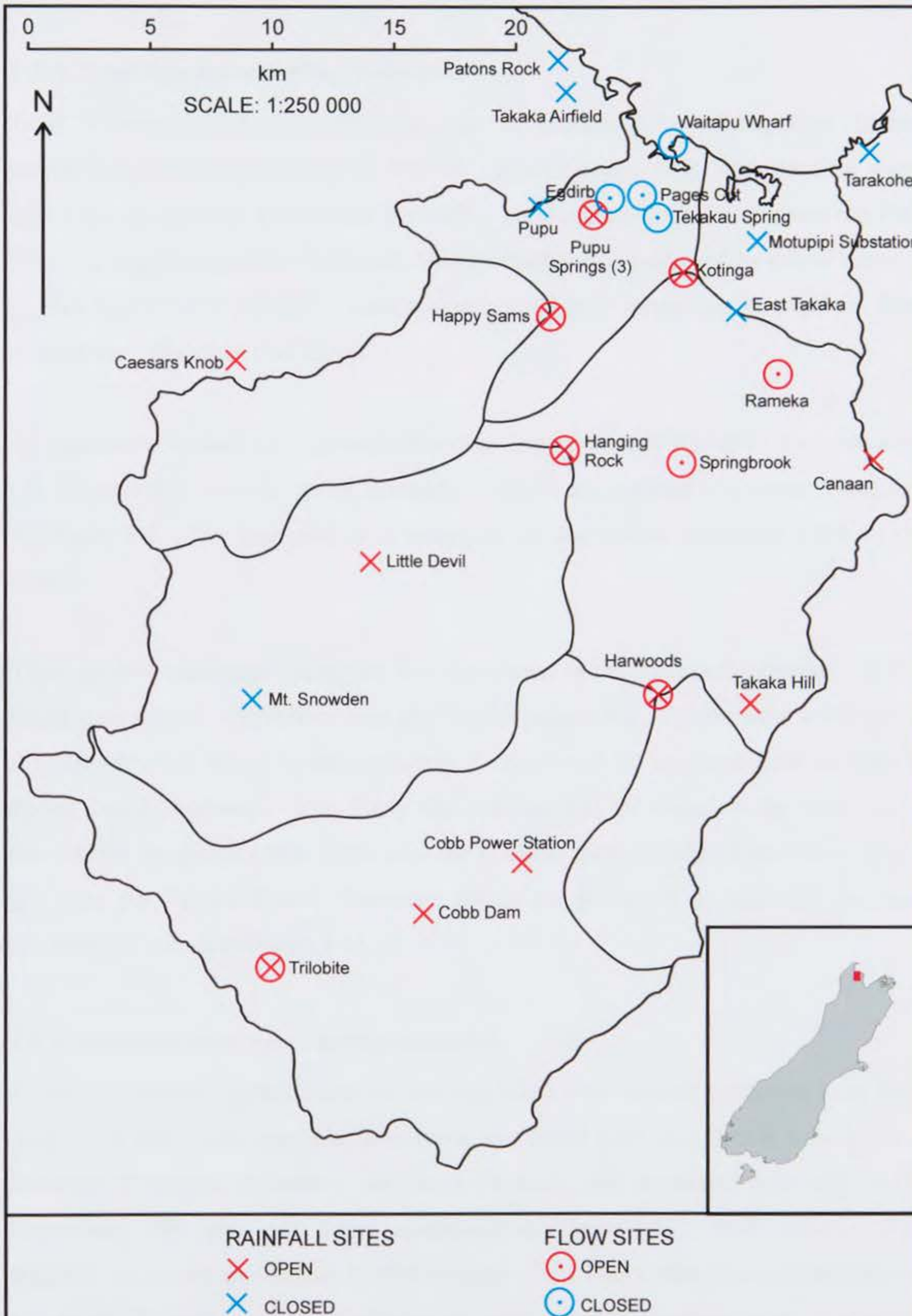


Figure 1.11. Location of open and closed rainfall sites and flow monitoring sites in the Takaka Catchment (for site details refer to Appendix B).

1.8.4 Springs monitoring network

Total Waikoropupu Springs discharge can be calculated by adding flow figures collected at the Springs River (N26 907399 - details Appendix B) with the total water take from the Salmon Farm (N26 908405). Total spring flow incorporates the Fish Creek Springs component. Fish Creek Springs discharge is measured by a flow recorder in Fish Creek (N26 905397). Data includes a variable proportion of overland flow derived from the upper Fish Creek.

An alternative method using groundwater data derived from WWD 6011-Balls recorder can be applied to generate spring discharge. Details are outlined in Chapter Three and Appendix F-I. The generated data record is for the period December 1994 to the present.

There are two additional spring fed sites monitored in the Takaka Catchment. Spring Brook data records extend from June 1991 to the present day. The recorder is situated at Elm Grove (N26 933312), and measures a component of overland flow as well as Spring Brook discharge. It is likely that the site will be closed in the near future. Records for the period 1984 - 1986 exist for Tekakau (N26 935398), a site that is spring fed from the Takaka River. Summary details are presented in Appendix B. Site locations are shown in Figure 1.11.

1.8.5 Groundwater monitoring network

There are records of groundwater fluctuations, taken over variable periods of time, for 6 monitoring sites: Balls and Hamama (with associated rock unit Arthur Marble), and Bennetts, C'Serneys, Jeffersons, and Grove Orchard (with associated rock unit Takaka Limestone). Of these, only 5 are presently open (Figure 1.12). Balls recorder (N26 902394), is located approximately 200 m south of the Fish Creek Springs, and directly reflects the fluctuations of the Waikoropupu Arthur Marble Aquifer system. Additional information for all sites (open and closed) is given in Appendix B, and site locations are shown in Figure 1.12..

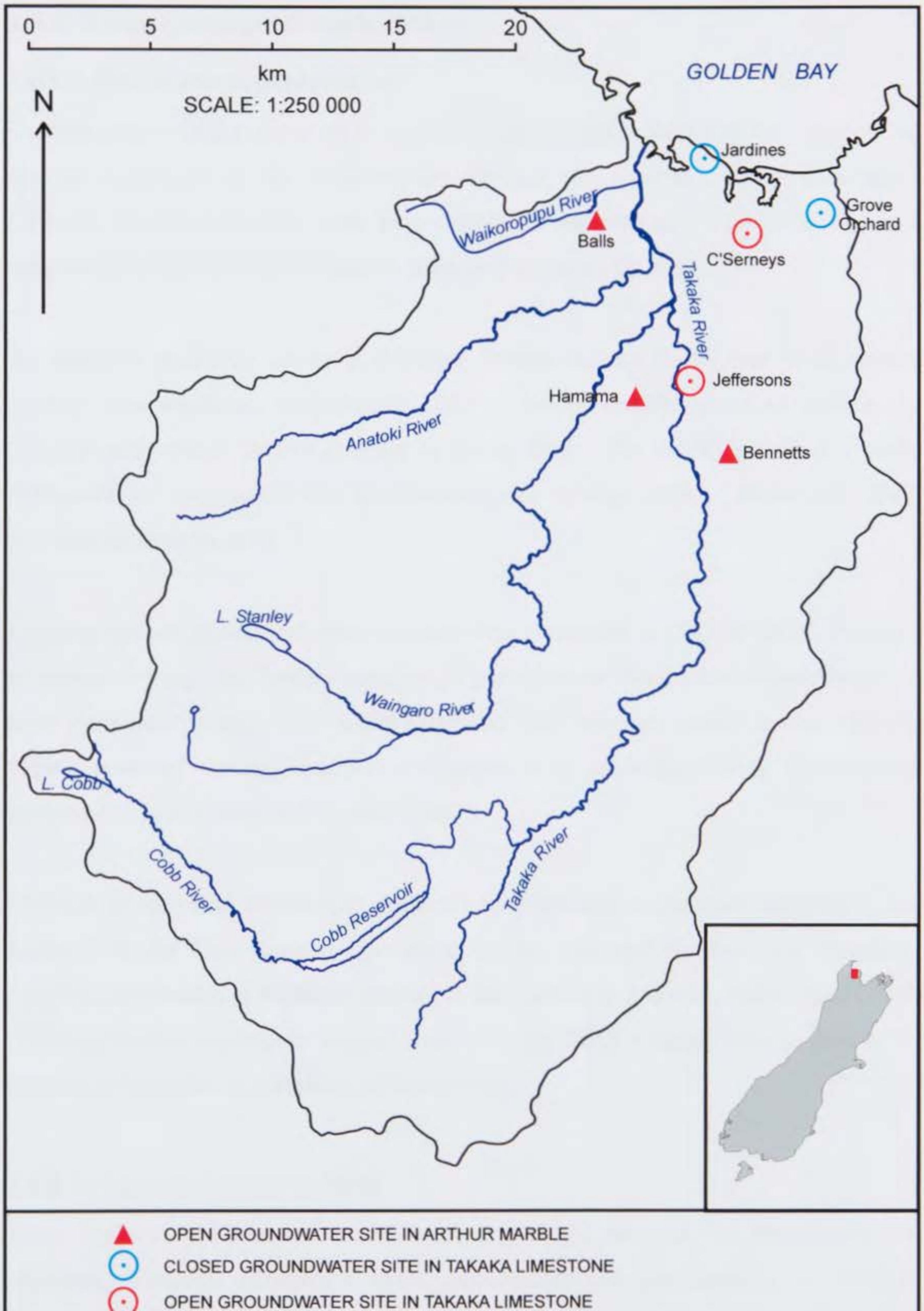


Figure 1.12. Location of groundwater monitoring sites in the Takaka Catchment

1.8.6 Hydrogeological exploration

1.8.6.1 Geophysical exploration

Onshore geophysical exploration in the Takaka Catchment is limited to two independent surveys conducted in the Waikoropupu Springs and Central-Lower Valley areas. Offshore data is available from past petroleum exploration. The following is a summary, with additional information presented in Appendix A-III.

An electrical resistivity survey at Bubbling Springs Salmon Farm, near Waikoropupu Springs, was conducted in February 1987 to assess whether proposed commercial developments would lead to changes in spring flow. The results provided a useful delineation of cover rocks near the Waikoropupu Springs outlets. Broadbent (1987) provides an interpretation.

Onshore shallow seismic reflection surveys were conducted in 1987 by DSIR, primarily to attempt to image the Tertiary structure, in particular the Takaka Limestone Aquifer. 3 lines were incorporated, 2 of which (101 and 102) provided useful results. Ravens (1990) provided the key interpretative paper, with some conflicting interpretation presented in Judd (1989) and Mueller (1987).

Offshore geophysical information collected by petroleum exploration companies, and lodged with the New Zealand Geological Survey, provided the basis for Thrasher's (1989) interpretation of Miocene faulting in the Tasman and Golden Bays. Judd (1989) combined available offshore seismic lines with the DSIR onshore seismic data in his analysis of Cenozoic deformation of Golden Bay.

1.8.6.2 Deep exploratory bores

Deep exploratory bores are useful in hydrogeologic analysis for determining the sequence, lithology, subsurface strata, occurrence, and configuration of aquifers. Limited onshore borehole data is available in the Takaka Valley. Onshore there are a total of 5 deep bores, each greater than 80 m deep. Three encounter Arthur Marble and two reach Takaka Limestone. A number of additional bores (between 20 and 60 m deep) exist. Full details of all available borehole information, including locations, is presented in Appendix A-II.

1.9 THESIS FORMAT

The format of this thesis follows the objectives outlined in section 1.2. This thesis is divided into seven chapters, with Chapter One as an introduction. Subsequent chapters are as follows :

Chapter Two *Geological and Hydrogeological Setting.* This chapter presents relevant geological and geomorphologic information, and stratigraphic and structural details for the Takaka Valley aquifer system. Details of hydrogeological setting include the delineation of aquifer extent, and the areal and vertical nature of aquifer boundaries.

Chapter Three *Hydrogeology of the Waikoropupu Arthur Marble Aquifer.* This chapter deals solely with the karst Arthur Marble Aquifer. It defines and assesses recharge sources and discharge zones. Investigation procedures include the determination of the relative flow losses and gains of contributing rivers and tributaries by the analysis of spring hydrographs. Additional information is given on fluctuations observed for the aquifer system.

Chapter Four *Hydrogeology of the Limestone and Gravel Aquifers of East Takaka and Takaka Township.* This is a composite chapter which involves analysis and assessment of the minor aquifers in specific areas of the Takaka Valley. Recharge and discharge assessment is intended to be descriptive rather than quantitative. Groundwater flow patterns and fluctuations are assessed where data allows.

Chapter Five *Water Chemistry and Quality of the Takaka Valley Aquifer System.* This chapter uses the existing surface water and groundwater database (held by the Tasman District Council) to provide a baseline assessment of water quality in the Takaka Valley aquifer system. Available data is of variable quality, and the assessment of individual aquifers will reflect this.

Chapter Six *Water Resource Evaluation of the Takaka River and the Takaka Valley Aquifer System.* Two issues have been selected for further study. The first is the derivation of a water balance for the Waikoropupu Arthur Marble Aquifer in the Takaka Valley. Previous attempts are reassessed and the previously assumed existence of submarine springs is re-evaluated. The second is an assessment of the effects of the Cobb power station of the Upper Takaka River regime and on aquifer recharge.

Chapter Seven *Summary and Conclusions.*

CHAPTER TWO : GEOLOGICAL AND HYDROGEOLOGICAL SETTING

2.1 INTRODUCTION

An appropriate level of geologic, geomorphologic, tectonic, and topographic information is necessary in order to explain the occurrence and movement of groundwater. Without this background knowledge any hydrogeological evaluation is incomplete. The objectives of this chapter are therefore:

- to delineate the extent and distribution of the primary hydrogeologic rock units (including confining layers), both onshore within Takaka Valley and offshore in Golden Bay,
- to identify the major tectonic episodes and structures (faults and folds) pertinent to aquifer development,
- to describe the geomorphic setting of the Takaka Valley, highlighting in particular those features ascribed to karstic development, and
- to describe the hydrogeologic setting, including aquifer nomenclature, aquifer description, extent of primary aquifers, nature of boundaries, and aquifer configuration.

Discussion is spatially restricted to the Takaka Valley and its immediate surrounds, namely the eastern and western foothills and Golden Bay; large parts of the Waingaro, Anatoki, and Cobb subcatchments are not included. The geologic discussion in this chapter concentrates on delineating the extent of aquifer and aquitard rock types. This leads into a discussion of the hydrogeological setting of aquifers in the Takaka Valley. A geological map of the Takaka Valley is presented in Figure 2.1. The geologic setting of the Takaka Catchment with respect to regional geology concepts was presented in Chapter One.

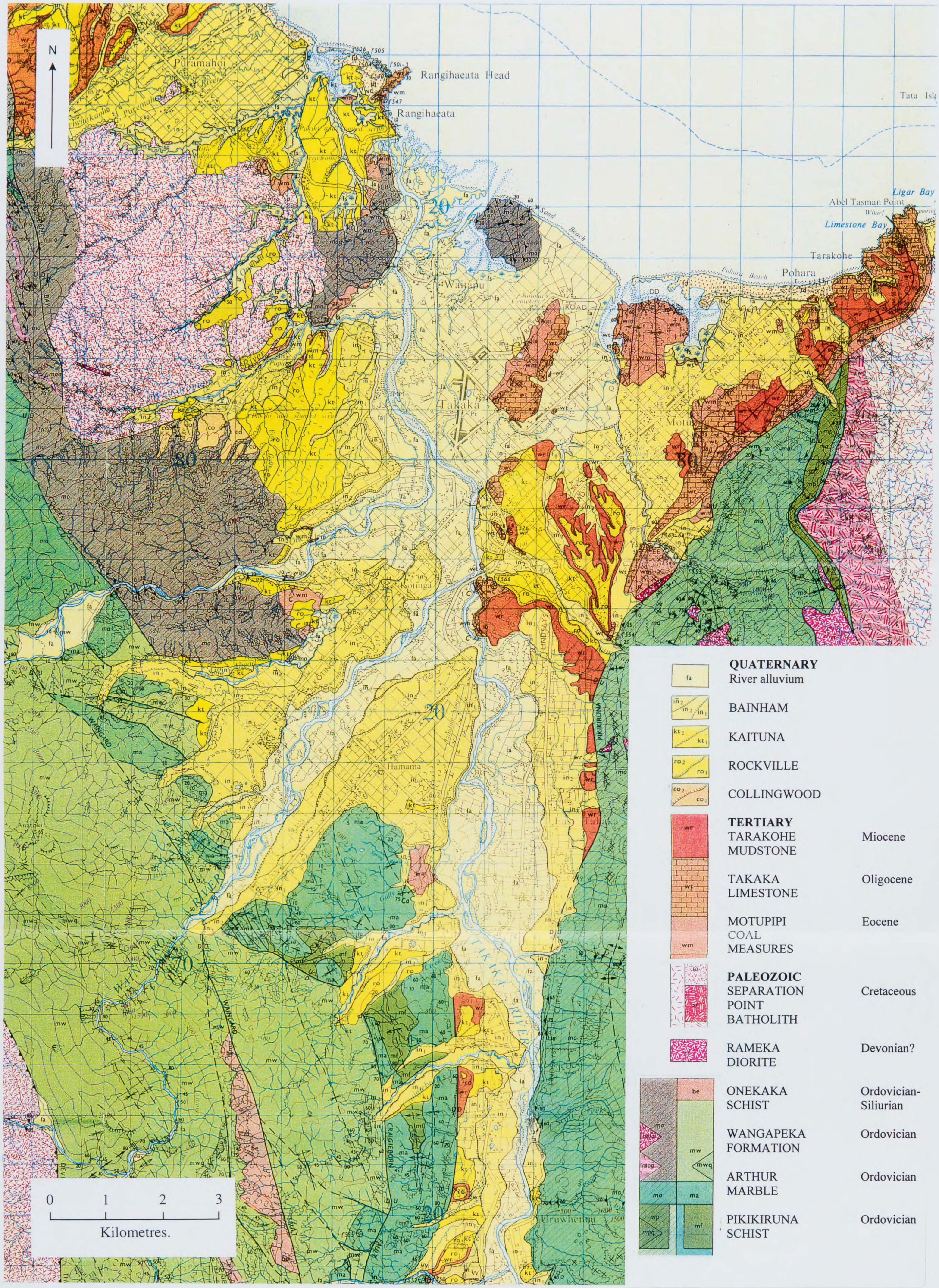


Figure 2.1. Geology of the Takaka Valley (Map taken from Sheet S8, Grindley 1971)

2.2 HYDROGEOLOGICAL STRATIGRAPHY

2.2.1 Arthur Marble

Arthur Marble, named after Mount Arthur and located on the southern boundary of the Upper Takaka Catchment (M27 833987), is the principal basement rock in the Takaka Valley. Paleontological dating constrains the age to Upper Ordovician - Silurian (Grindley 1971). The main exposures are along the Pikikiruna Range and in the foothills of the western flanks of the Anatoki and Lockett Ranges (Figure 2.1). Additional important but localised outcrops have been identified at Waitui Stream and Waikoropupu River

Shelley (1981, 1984, 1991) describes in detail the metamorphic nature and structure of Arthur Marble in the Pikikiruna Range. Increased metamorphism is observed from west to east (Grindley 1971). Eastern outcrops (in the Pikikiruna Range and the eastern foothills) are described as grey-white marble with thin schist, compared with western outcrops which are grey to white crystalline limestone with thin argillite (Grindley 1971).

Takaka Valley Arthur Marble is part of a discontinuous band of marble which occurs at broadly similar stratigraphic positions in Northwest Nelson, extending from Mt. Owen in the south to Collingwood in the north (Coleman 1981, Grindley 1971, Bishop 1971). Arthur Marble is extensive both underneath the Takaka Valley and immediately offshore. Total outcrop coverage within the Takaka Valley, the surrounding foothills, and the karst plateau, is approximately 60 km^2. The vertical extent underneath the Takaka Valley is unknown, but it is assumed to be of the order of hundreds of metres. Coleman (1981) recognised a complete 1500 m stratigraphic section of Arthur Marble between the middle branch of the Owen River and the Fyfe River. In the Takaka Valley and Golden Bay, Arthur Marble is unconformably overlain by the Tertiary sequence, either Eocene Motupipi Coal Measures or Oligocene Takaka Limestone (Figure 2.1).

2.2.2 Onekaka Schist and Wangapeka Formation

Silurian Onekaka Schist (which crops out at Waitapu Hill and in the north-western section of the Takaka Valley) and Wangapeka Formation (which crops out on the western foothills) (Figure 2.1) are minor basement rocks of the Takaka Valley. Complex relationships exist between these Paleozoic rocks and the overlying Tertiary sediments, especially along the western side of the valley. Both onlapping relationships and faulted contacts are observed: detailed geological descriptions are given in Grindley (1971), Bishop (1971) and Coleman (1981).

2.2.3 Motupipi Coal Measures

The Motupipi Coal Measures (regionally known as Brunner Coal Measures) are a lateral correlative of the southern Taranaki Mangahewa Formation (King and Thrasher 1996). They consist of fining upward sequences of cross-bedded sandstone which pass into carbonaceous mudstone, and they contain thin coal seams (Nathan *et al* 1986). Leask (1980) renamed the unit the Brunner Coal Measures, and separated the formation into two members. He recognised five facies: alternating sand fine sandstone and mudstone, bioturbated muddy sandstone, cross bedded sand, thick bedded sand and gravel, and alternating sandstone/conglomerate/mudstone. Not all facies or members are present at all the localities to be discussed. Coal measures are Eocene in age, with basal facies deposited in Bortonian-Kaiatan, and with more widespread deposition in the Runangan-Whaingaroan (Appendix A-I).

Prominent outcrops occur along Dry River (N26 975364-N26 971367), at the foot of the Pikikiruna Scarp, and in cliffs and on the beach east of the Rangihaeata Headland (base of section is at N25 920434). These extensive thicknesses (350 m and 190 m respectively) include basal coal measure sequences (for example facies mb_1 and mb_2), but the actual base is not seen. Type locality for Motupipi Coal Measures is at the Motupipi estuary, on both sides of Trig DD (N25 972411). Other outcrops, such as those shown in Figure 2.2, occur along the Pupu Springs Road.

Onshore distribution of coal measures is restricted to north of Hamama, with the most southern outcrop occurring between Pigville Gully and Spring Brook (Figure 2.1).

Offshore distribution can only be inferred from isopach maps (King and Thrasher 1996, Nathan *et al* 1986). These maps suggest that the Motupipi Coal Measures do not thin offshore into the immediate Golden Bay. Leask (1980) notes that pre Oligocene sediments may be thin on the 40 km^2 plateau of Golden Bay. From available information, this thesis therefore assumes that a variable thickness of Motupipi Coal Measures extends offshore.

Vertical thickness is variable across the Takaka Valley, and ranges from 0 to approximately 350 m. Substantial thicknesses (greater than 300 m) are found only in the eastern valley, for example near Dry River. Geophysical interpretation (Ravens 1990, Judd 1989) suggests that the Motupipi Coal Measures are of variable thickness from east to west; the total thicknesses between Waitapu and Birch Hill (500-2000 m south of the present day Golden Bay coastline) are between 240 m and 350 m (Appendix A-III). A drillhole (148.6 m in depth) located between Fish Gully and the Anatoki River, on the western side of the valley (N26 911379), is confirmed to have encountered Motupipi Coal Measures (Mueller 1992). Assessment is based partly on the presence of quartz (quartzite) and minor deeply leached granite. These details are consistent with descriptions of basal coal measures in Grindley (1971) and Leask (1980). Total thickness encountered at the Fish Gully drillhole is of the order of 128 m.

2.2.4 Takaka Limestone

Takaka Limestone conformably overlies the Motupipi Coal Measures north of Hamama, and unconformably overlies Arthur Marble south of Hamama. The formation is Oligocene in age and typically hard, with little primary porosity (Nathan et al 1986). Leask (1980) describes Takaka Limestone a pure, hard, flaggy limegrainstone or packstone, basally rich in terrigenous sand. He identifies eight facies: glauconitic limestone, calcereous conglomerate and sandstone, mollusc lime packstone, bryozoan-bivalve lime grainstone, bryozoan lime grainstone, algal lime packstone, fine sandy calcarentire, and foram-echinoderm lime grainstone. Not all facies are present at all the localities to be discussed.

Prominent outcrops include the footslopes of the Pikikiruna Range from East Takaka to Tarakohe, Paynes Ford, and Birch Hill. The type locality is at the old cement works at Tarakohe, just outside the north eastern boundary of the field area, and is shown in Figure 2.3.

Onshore the Takaka Limestone is extensive, and is assumed to have been deposited over the entire Takaka region (prior to the formation of the Takaka Valley faulted depression). The absence of Oligocene sediments from certain sections in the Takaka Valley is more likely to be due to later erosion than to non-deposition. Offshore the lateral correlative of the Takaka Limestone, the Tikorangi Formation (Thrasher and King 1996), is present in the following southern Taranaki wells: Surville 1, Tasman 1, Nth Tasman 1, and Fresne 1 (King and Thrasher 1996). Isopach maps (King and Thrasher 1996) do not indicate any break in deposition, and the presence of limestone in offshore wells suggests that limestone would extend offshore into the present day Golden Bay. Judd (1989) interprets the presence of limestone at a depth of 1000 m at line FS-11 (seismic line), which is situated 11 km off the coast of present day Golden Bay.

Vertical thickness of the Takaka Limestone is shown in Figure 2.4, taken from Leask (1980). The maximum thickness in the valley is assumed to be 60 m (Figure 2.4); in the regions offshore the thickness is generally less than 50 m (King and Thrasher 1996). Total limestone thickness can only be deduced from three drillholes situated in the Central Takaka and Motupipi areas; observed thicknesses are 63 m (WWD 6612), 52 m (WWD 6410), and 19.5 m (WWD 6422). According to Grindley (1971) Takaka Limestone thins to 15-30 m in the western part of the Takaka Valley. Drillhole evidence suggests that in certain areas limestone is not present at all (for example WWD 6010); additional drillhole information would be required to accurately delineate the western extent of Takaka Limestone. Full details of drillholes are provided in Appendix A-III.

2.2.5 Tarakohe Mudstone

Tarakohe Mudstone conformably overlies the Takaka limestone, and is unevenly distributed throughout the Takaka Valley (Figure 2.1). It has an assigned age of early-

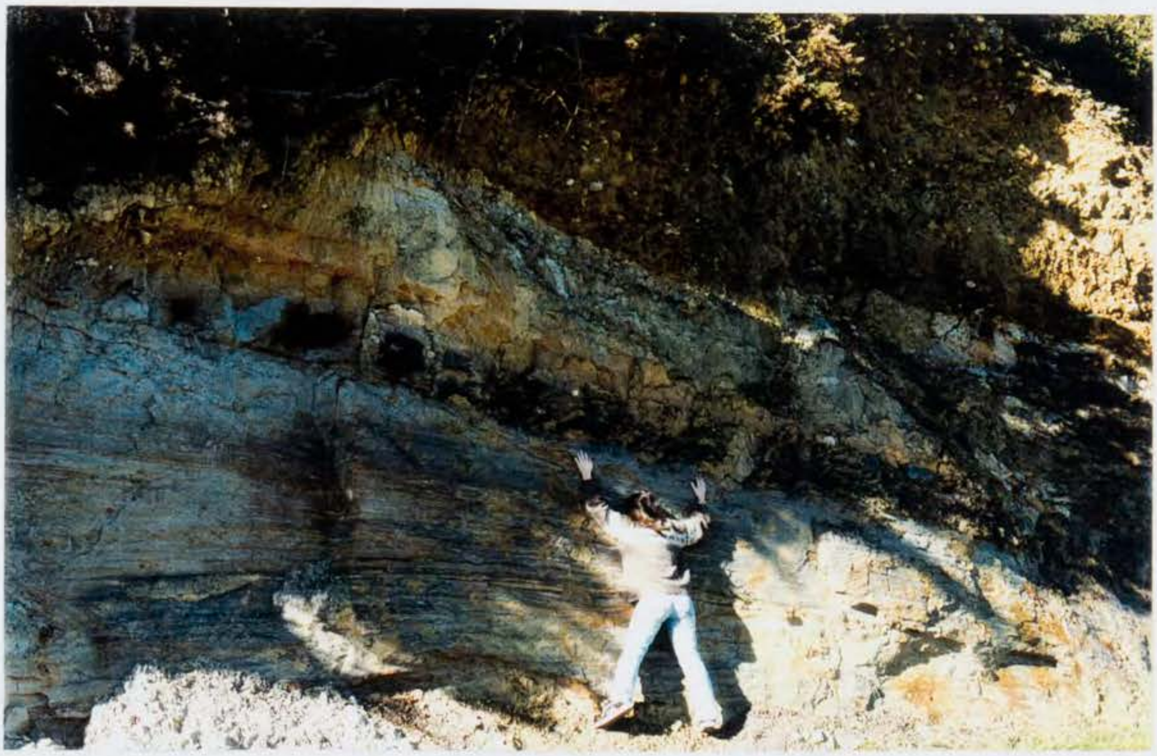


Figure 2.2. Motupipi Coal Measures crop out along road cuts of Pupu Springs Road (N26 907 398)

Figure 2.3. Takaka Limestone overlain by Tarakohe Mudstone at the abandoned Tarakohe cement works

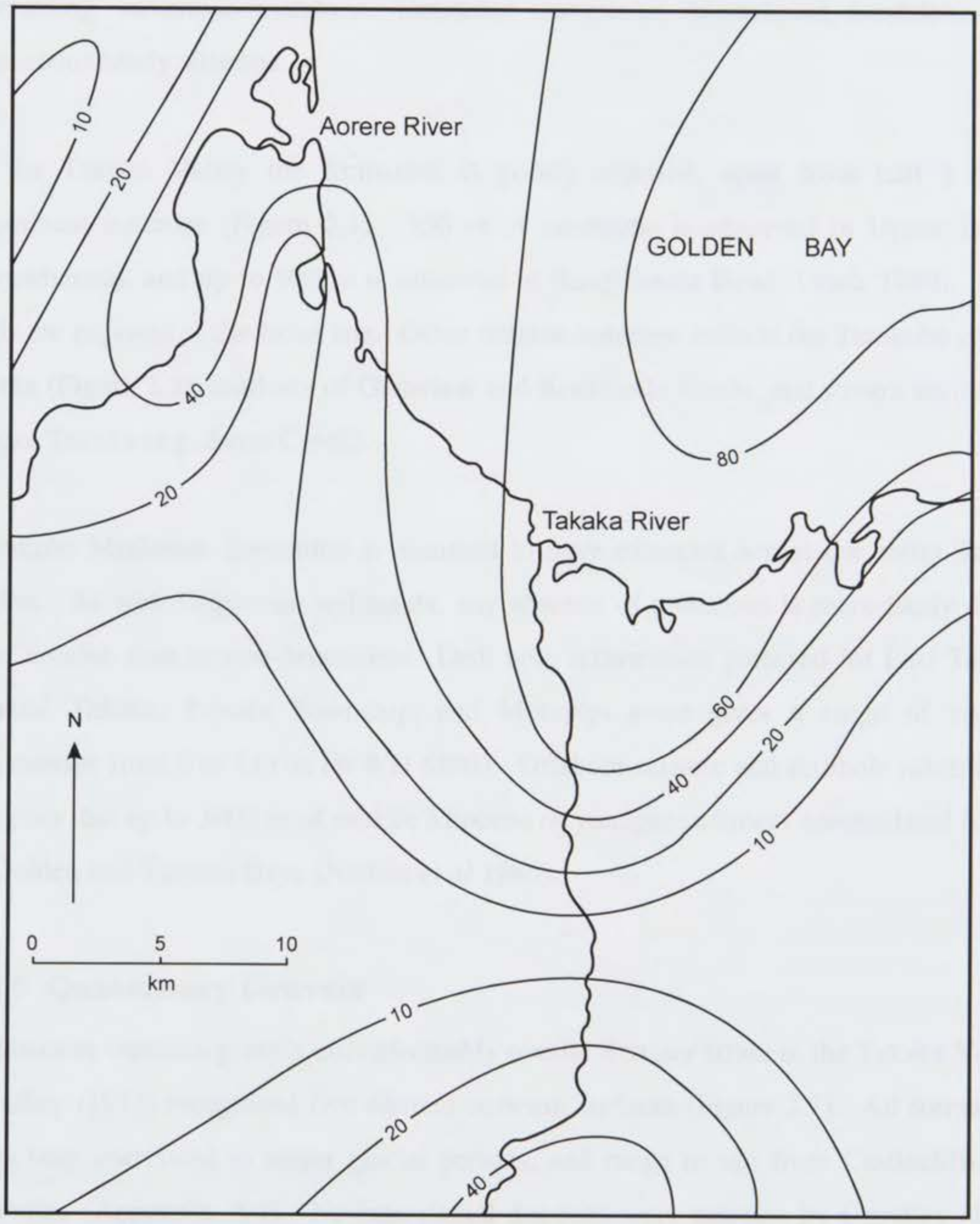


Figure 2.4. Takaka Limestone thickness contours in Golden Bay (all contours in metres)
(from Leask, 1980)

Middle Miocene (Leask 1980), and consists predominantly of massive grey-brown mudstone, with variable proportions of granite derived sands (Nathan et al 1986). Leask (1980) recognises six facies: glauconitic calcereous sandstone, massive mudstone, alternating sandstone/mudstone, laminated sandstone, bioturbated sandstone, and micaceous sandy siltstone.

In the Takaka Valley the formation is poorly exposed, apart from half a dozen prominent outcrops (Figure 2.1). 350 m of mudstone is observed in Upper Takaka (Uruwhenua), and up to 900 m is observed at Rangihaeata Head (Leask 1980). Basal beds are exposed at the latter site. Other notable outcrops include the Tarakohe cement works (Figure 2.3), roadcuts of Glenview and Rocklands Roads, and stream sections in Upper Takaka (e.g. Sams Creek).

Tarakohe Mudstone deposition is assumed to have extended across the entire Takaka region. As with Oligocene sediments, any absence of mudstone is more likely due to later erosion than to non-deposition. Drill hole information gathered for East Takaka, Central Takaka, Takaka Township, and Motupipi areas gives a range of onshore thicknesses from 0 to 114 m (WWD 6808). Offshore seismic and drillhole information suggests that up to 3000 m of middle Miocene or younger sediment accumulated locally in Golden and Tasman Bays (Nathan *et al* 1986).

2.2.6 Quaternary Gravels

Pleistocene outwash gravels unconformably overlie Tertiary strata in the Takaka Valley. Grindley (1971) recognised five distinct outwash surfaces (Figure 2.1). All formations have been correlated to major glacial periods, and range in age from Castlecliffian to Aranuian (Appendix A-I). No interglacial deposits were mapped by Grindley (1971) river alluvium being the only postglacial deposit mapped. Detailed description of all Quaternary gravel deposits found in the Takaka Valley is given in Table 2.1.

Holocene river alluvium deposits cover the mid valley from Lindsays Bridge to the coastline (Figure 2.1). They are of variable thickness, and are typically of the order of 10 m. Additional important deposits, especially in the East Takaka area, are those of the

Formation	Age (Stage)	Description
Bainham	Oturian - Otiran	Almost unweathered, rounded gravel underlying lowest aggradational terraces of Takaka and Aorere Valleys; two terrace levels 50ft apart. Prominent degradational terrace. N iron pan developed.
Kaituna	Terangian - Oturian	Slightly weathered (pale yellow-brown), coarse gravels underlying intermediate terrace. Two terrace levels. Pebbles unweathered. Slight iron pan. Loess.
Rockville	Waiwheran - Terangian	Moderately weathered (yellow-brown) coarse gravel underlying higher extensive terraces. Two terrace levels. Most pebbles unweathered. Thin iron pan. Loess.
Collingwood	Castlecliffian - Waiwheran	Strongly weathered (brown-red) coarse gravel underlying highest extensive terraces. Two terrace levels. Most pebbles weathered. Iron pan and leached pakihi soil.

Table 2.1. Description of Quaternary deposits. From Grindley (1971)

two youngest outwash surfaces of the Bainham Formation (in_1-in_2). Minimum thickness of these deposits is of the order of 6 m (Appendix A-II).

The correlation of Quaternary Gravels in the Takaka Valley is based on the degree of weathering, the colour of weathered material, the stages of podolisation with development of iron pan, and the altitudes and reconstructed profiles of terraces (Grindley 1971). Apart from the original mapping by Grindley (1971) little further investigation of Quaternary geology in the Takaka Valley has been carried out.

2.3 TECTONIC AND STRUCTURAL SETTING

2.3.1 Phases of tectonic activity in the Takaka Valley

A number of distinct phases of folding and fault movement have been identified in the Takaka Valley. Golden Bay and neighboring Tasman Bay are southern continuations of a fault and fold belt portion of the Taranaki Basin (Thrasher 1989). Most of the existing literature on structural investigation incorporates offshore drillhole results and seismic information. Discussions of tectonic setting in this section are concerned with events pertinent to the Takaka Valley, and therefore will incorporate information derived from regional based studies, such as Judd (1989) and Thrasher (1989).

Multiple deformation events occurred in the Ordovician and Siliurian (Jongens 1997, Roser et al 1996), and resulted in the complexly folded Ordovician Arthur Marble. Evidence for two Paleozoic deformational phases at Upper Takaka is given in Hickey (1986), and Shelley (1981, 1984). Outcrops in the Pikikiruna Range, characterised by moderately inclined to recumbant folds, were determined by Shelley (1991) to be Siliurian-Devonian.

A period of relative tectonic quiescence during the Late Cretaceous to Early Tertiary resulted in the formation of the Northwest Nelson peneplain (Chapter One, Figure 1.4). Tertiary rocks in the Takaka Valley lay on a well developed surface that dipped gently (less than 10°) towards the southeast or east (Shelley 1991). Major faults (which are detailed in section 2.3.2) were not active during the Eocene-Oligocene; movement of major faults (as well as minor faults) occurred in the latest Miocene-early Pliocene.

Judd (1989) found evidence for some fault movement well into the Pleistocene, based on measured dips between 4°-10° of Rockville outwash surfaces (300000 year-old terraces), and on minor deformation of the basal Pleistocene horizon offshore. Additional evidence for Pliestocene movement can be found in Williams (1982), who dated speleothems from caves in Takaka Limestone. Bainham (in_I and in_{II}) surfaces are undeformed, indicating no Holocene movement.

2.3.2 Important faults and fold structures in the Takaka Valley

2.3.2.1 Pikikiruna Fault

The Pikikiruna Range is bounded on it western side by the Pikikiruna Fault, which is an important, yet poorly exposed, fault structure in the east of the Takaka Valley (Figure 2.1). Originally described by Wellman (1945) as a monocline fault, it was later redescribed as a reverse (Grindley 1971) or reverse-splayed fault (Judd 1989).

The north end of the fault trends northeast-southwest, the mid section is straight, pronounced, and trends north-south, while the southern portion (in the Takaka Valley) reverts back to a northeast-southwest trend (Grindley 1971, Judd 1989). Where exposed, the fault dips between 35°-40° to the east (Judd 1989, Thrasher 1989, Mueller, cited in Shelley 1991). In the north and centre of the area, Tertiary beds adjacent to the fault are abruptly bent to near vertical attitudes, and no major reorientation of the marble structure is apparent (Shelley 1991). Maximum vertical offset is of the order of 1000 m (Judd 1989). This is reflected in the steeply rising Pikikiruna Scarp, which lifts the peneplain surface from below the Takaka Valley to the karstic plateau of Canaan Downs above the Pikikiruna Range (Shelley 1991).

Based on interpretation of offshore seismic data and drill hole information, Thrasher (1989) constrains the reverse movement on the Pikikiruna Fault to the latest Miocene-Pliocene period. Onshore seismic analysis (Raven 1990, Judd 1989) concurs with Thrasher's (1989) findings. It constrains the start of reverse faulting on the Pikikiruna Fault to after the deposition of the Tarakohe Mudstone, as the mudstone displays deformation to the same extent as the underlying Tertiary formations.

2.3.2.2 East Takaka Fault zone and Motupipi Fault

The East Takaka Fault system comprises five distinct thrust faults and possibly several minor ones; the extent of the system is shown in Figure 2.5 and Appendix A-III. The original identification of the system was based on onshore seismic data (Ravens 1990, Appendix A-III); further interpretation is found in Judd (1989) and Mueller (1987).

The East Takaka Fault system appears to trend north-south and has no surface expression; it interrupts basement (Arthur Marble), and the overlying Tertiary sediments, but not the Quaternary glacial and alluvial deposits. Offsets on the multiple faults range from 10-40 m (Judd 1989). To the north of the valley, near the present day coastline, faulting is reduced in intensity and folding is more dominant.

The timing of fault movement is assumed to be late Miocene (Ravens 1990), based on disruption to Tarakohe Mudstone. Alternatively it could have developed at a later stage (i.e. post Miocene), as a result of intense constriction between the Pikikiruna and Golden Bay Faults (Judd 1989).

The Motupipi Fault was identified and named by Judd (1989). He proposed a blind thrust under Trig DD (N25 971411) based on field mapping and geophysical evidence (Figure 2.5). Offshore the Motupipi Fault would extend into Golden Bay and was assumed to connect to the east dipping thrust running though the east side of Golden Bay (Judd 1989). Onshore the Motupipi Fault has been correlated with the east dipping thrusts of the East Takaka Fault system (Judd 1989). Fault movement is likely to coincide with the activation of the late Miocene East Takaka Fault system.

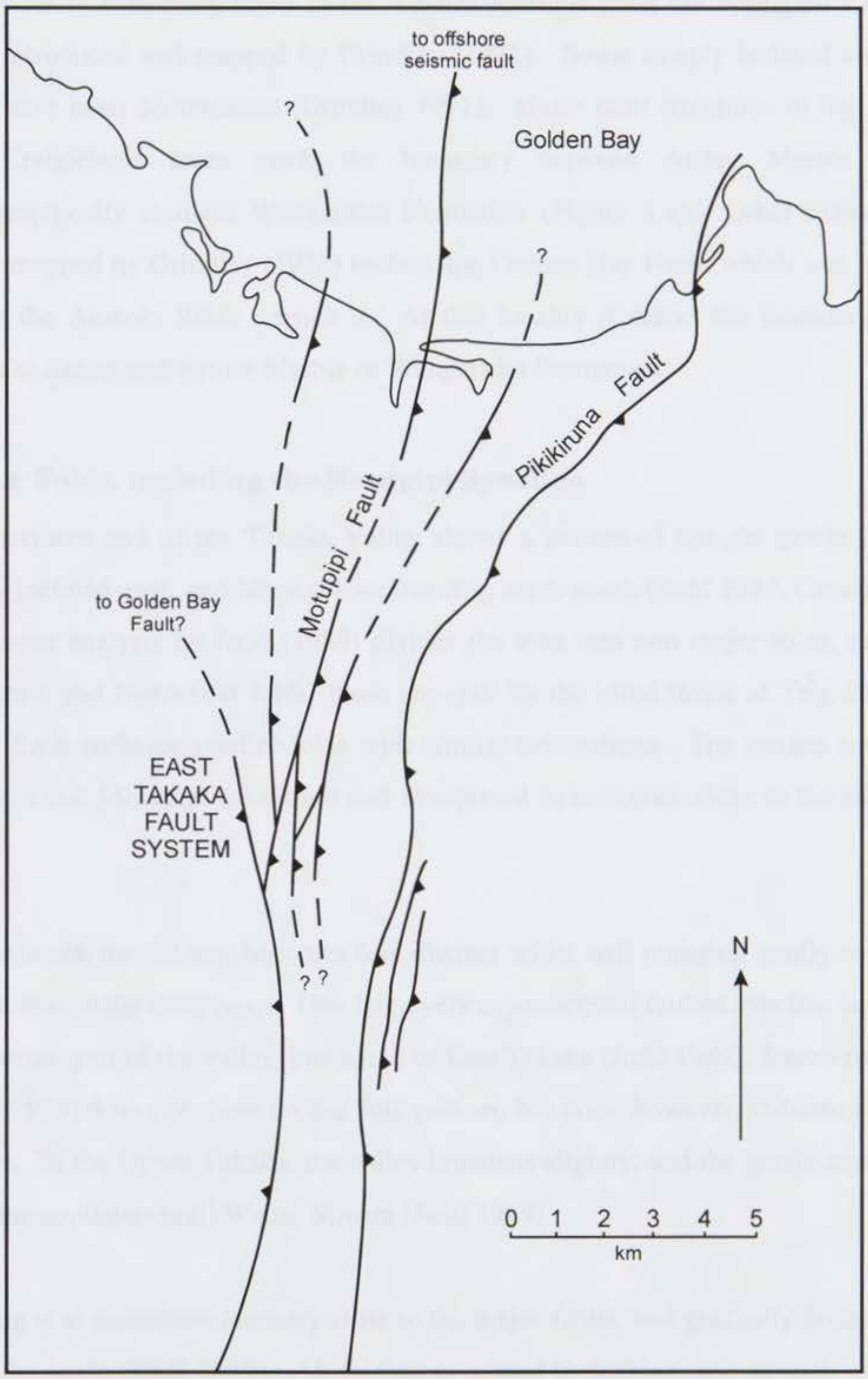


Figure 2.5. Extent of the East Takaka Fault system interpreted by Judd (1989).
Dashed lines represent inferred fault sections.

2.3.2.3 Western Faults

A number of subsidiary faults in the western foothills from the Waingaro River south were introduced and mapped by Grindley (1971). Some steeply inclined and upright folds have been documented (Grindley 1971). Major fault structures in the Waingaro and Craigieburn areas mark the boundary between Arthur Marble and the stratigraphically younger Wangapeka Formation (Figure 2.1). Other major western faults mapped by Grindley (1971) include the Golden Bay Fault, which was mapped to where the Anatoki River crosses it. At this locality it marks the boundary between Onekaka Schist and Arthur Marble or Wangapeka Formation.

2.3.2.4 Folds, including the Motupipi Syncline

The northern end of the Takaka Valley shows a pattern of upright gentle folds with gently inclined axes, and hinge planes trending north-south (Judd 1989, Grindley 1971). Stereo-net analysis by Judd (1989) divides the area into two major folds, namely the Northeast and Northwest folds; these are split by the blind thrust at Trig DD (Figure 2.6). Each includes smaller folds with similar orientations. The eroded anticlines at Waitapu and Motupipi are closed and interpreted to terminate close to the shore (Judd 1989).

To the south the folding becomes less distinct while still plunging gently southwards, until it eventually disappears. One large very asymmetrical faulted syncline is present in the narrow part of the valley, just south of East Takaka (Judd 1989). Stereo-net analysis (Judd 1989) does not show a clear fold pattern, but does, however, indicate a northerly plunge. In the Upper Takaka, the valley broadens slightly, and the gentle asymmetrical syncline continues until Waitui Stream (Judd 1989).

Folding is at maximum intensity close to the major faults, and gradually decreases away from the faults (Judd 1989). All folding is related to faulting, and as such would have occurred at the same time as faulting.

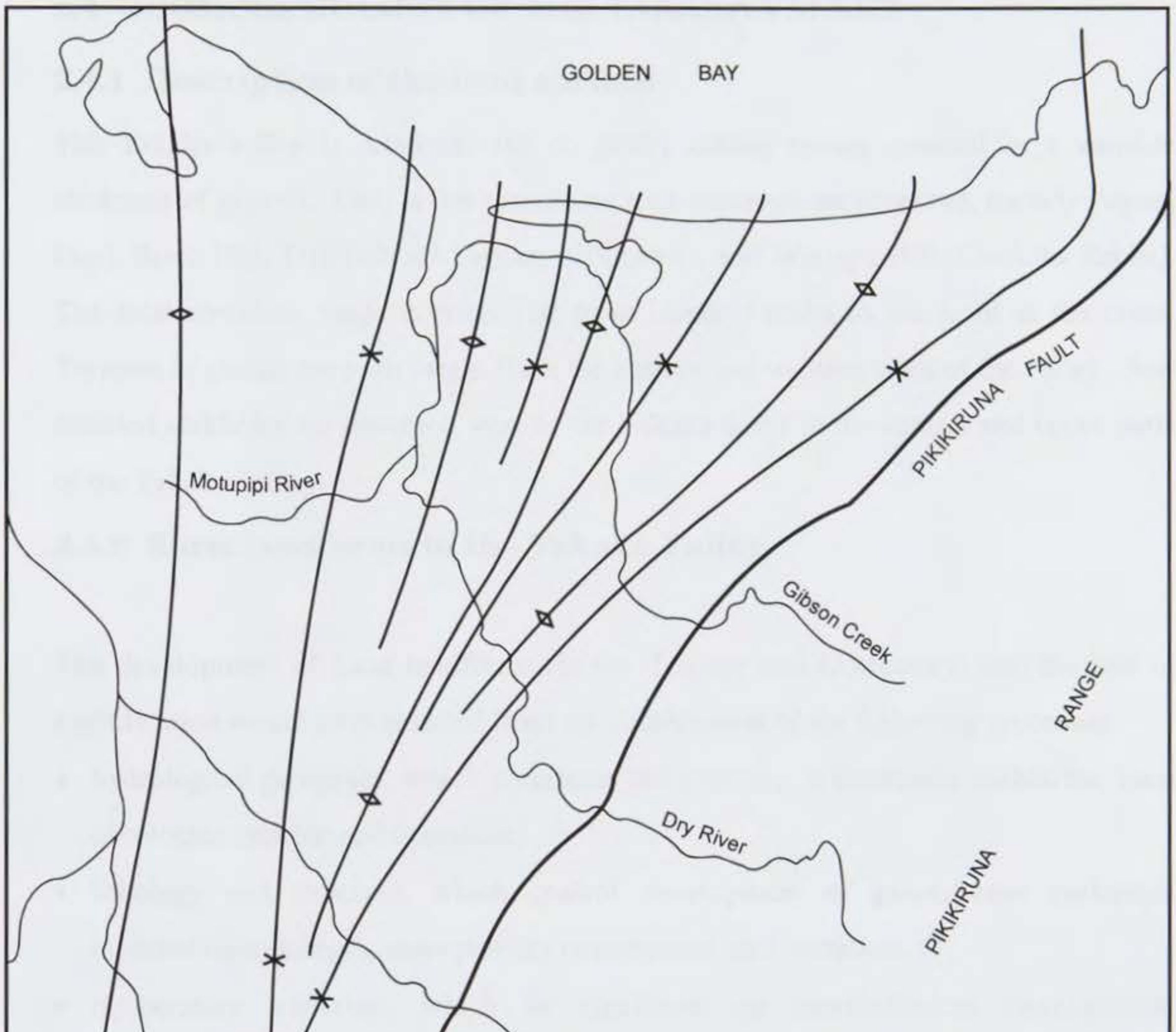


Figure 2.6. Structure of Tertiary sediments in the Lower Takaka Valley (adapted from Judd, 1989)

2.4 GEOMORPHOLOGY OF THE TAKAKA VALLEY

2.4.1 Description of the land surface

The Takaka valley is relatively flat to gently rolling terrain covered in a variable thickness of gravels. Only a few prominent rock outcrops are observed, namely Paynes Ford, Birch Hill, Trig DD (all Tertiary sediments), and Waitapu Hill (Onekaka Schist). The total elevation range is from 120 m at Upper Takaka to sea level at the coast. Terraces of glacial outwash origin flank the eastern and western sides of the valley. Soil mantled sinkholes are observed west of the Takaka River in the central and upper parts of the Takaka Valley.

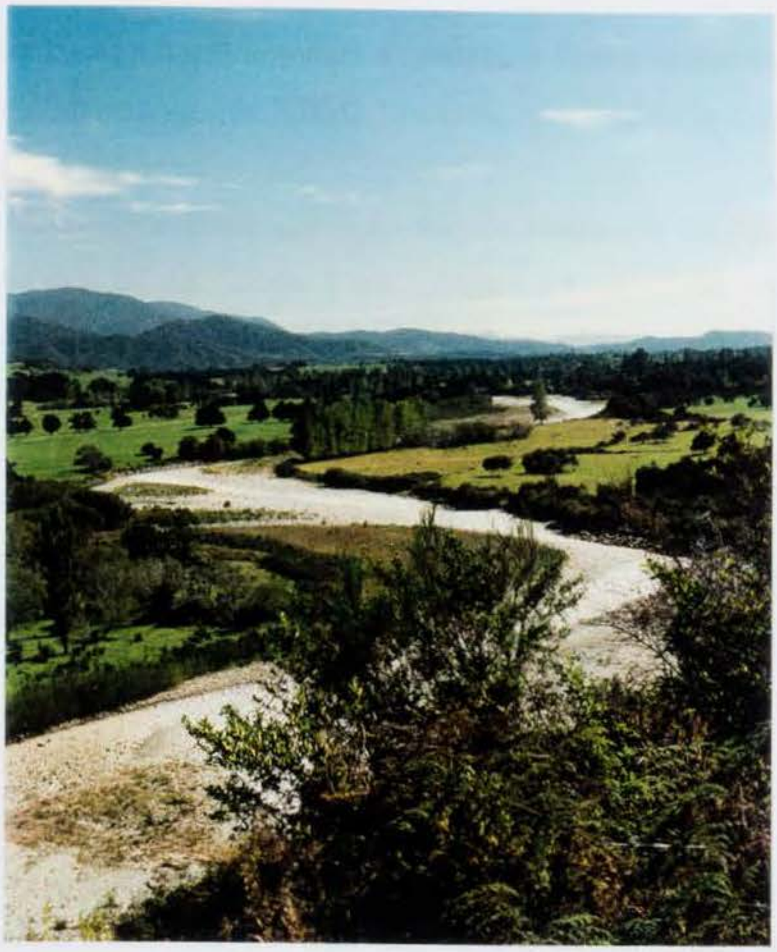
2.4.2 Karst landforms in the Takaka Valley

The development of karst landforms (in the Tertiary and Quaternary) and the rate of karstification would have resulted from the combination of the following processes:

- hydrological processes, which determine the location of landforms within the karst lithologies (marble and limestone),
- lithology and structure, which control development of groundwater pathways, inherent rock strength, susceptibility to corrosion, and corrasion,
- temperature variation, which is significant in morphological development, influencing the rate of chemical reactions, biochemical reactions, and water balance (i.e. evapotranspiration), and
- annual runoff, which influences the rate of landscape development (Ford and Williams 1989).

White (1988) or Ford and Williams (1989) should be consulted for detailed discussions on development of surface karst landforms.

The Takaka Valley is an example of a fluvio-karst environment. The most prominent features are the sinking streams and the Takaka River. The Takaka River loses flow along an 8 km gravel covered river stretch between Lindsays Bridge and upstream of Stoney Creek (Figure 2.7). For approximately 100 days a year the river in this section runs dry (in full or in part). It can be classified as an influent allogenic river (Ford and



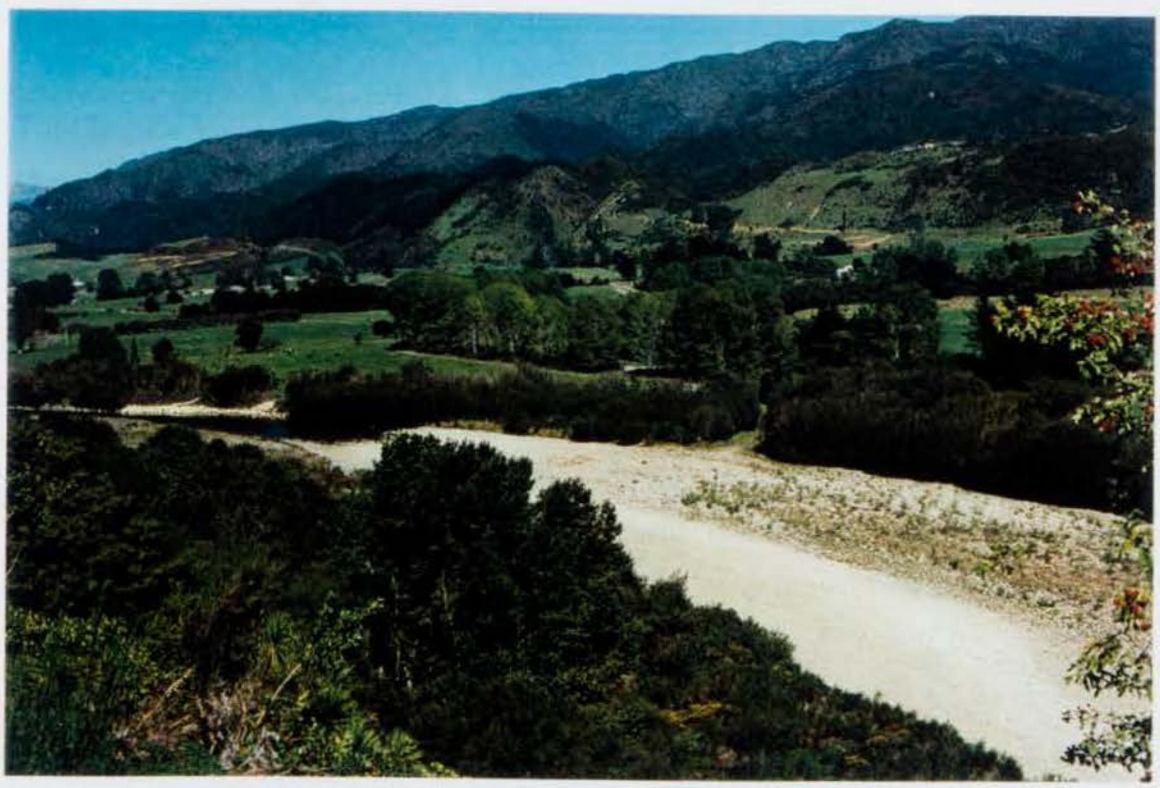


Figure 2.7. The influent allogenic Takaka River (photos taken 20 March 1998)

Williams 1989), because it still maintains a continuous channel downstream of the loss zone. Detailed examination of the Takaka River loss zone is given in 3.2.3.1.

Scattered karst depressions (dolines, or sinkholes) are observed in the Upper and Central Takaka Valley, west of the Takaka River. Figure 2.8 shows the extent of doline development. They are irregularly spaced, and are likely to have resulted from either the collapse, or the solution of the marble or limestone, with the subsequent collapse of overlying Tertiary sediments and gravels. The typical morphology of a ponded sinkhole observed in the Central Valley is shown in Figure 2.9. Many depressions, however, have permeable bottoms and do not pond water. Development is more subdued than in the karst development of the Takaka Hill plateau.

2.5 HYDROGEOLOGICAL IMPLICATIONS

2.5.1 Hydrogeologic implications of lithology

Geology has an important influence on any hydrogeological setting: it controls potential aquifer boundaries, determines the areal and vertical aquifer extent, and influences aquifer development through lithological characteristics.

The Takaka Valley aquifer system is comprised of three water bearing formations: Ordovician Arthur Marble, Oligocene Takaka Limestone, and Quaternary Gravels. Arthur Marble is the major aquifer, Takaka Limestone is the minor aquifer, and both are karstic in nature. Quaternary Gravels, whilst extensive and important, do not occur in vertical distributions such as those observed in the Waimea, Moutere, or Motueka plains. There are two principal aquitards or confining layers: the Motupipi Coal Measures, which act as an impervious layer unconformably overlying basement Arthur Marble and underlying Takaka Limestone, and the Tarakohe Mudstone, which conformably overlies Takaka Limestone and is the lower impervious boundary for the unconformably overlying Quaternary Gravels.

In order to define the nature of vertical boundaries (which are discussed in section 2.6.2) it is important to have established the areal extent of confining formations. As an example, the extent of Motupipi Coal Measures onshore controls the boundary between

Figure 2.9. Typical morphology of a ponded sink hole in the Upper Takaka Valley (N26 945264)

Figure 2.8. Distribution of sink holes (both ponded and free draining) along the western margin of the Takaka River in Upper Takaka (1:25 000)

the unconfined and the confined karstic aquifers, whilst the presence of coal measures offshore has important ramifications for the existence of submarine springs issuing from the main karst aquifer. On the western side of the valley, Wangapeka Formation crops out where the Anatoki and Waingaro Rivers flow, and it provides an impervious basement.

2.5.2 Hydrogeological implications of tectonic and structural setting

Both the understanding of structural setting and the recognition of deformation history are critical in any hydrogeological investigations. They have a profound influence on topography, recharge/discharge style, groundwater process, and water flow.

It is reasonable to assume that the Tertiary peneplain (i.e. the period of tectonic quiescence) provided a suitable environment for the development of a subterranean cave system in Arthur Marble. During subaerial exposure, dissolution of Arthur Marble by surface and groundwater would have been possible (Mueller 1991). The early Tertiary paleocave system in Arthur Marble would have been reactivated and highly modified in the Pliocene and Pleistocene (Mueller 1991).

Tectonic activity and accompanying erosion in the Pliocene (Nathan et al 1986), and further uplift and activity in the Pleistocene (Judd 1989), is thought to be responsible for the reactivation of the karst systems in Arthur Marble and activation of the karst systems in Takaka Limestone. Lower sea levels during periods of the Pleistocene would have resulted in hydrostatic pressures which enabled the reopening, flushing, and extension of the karst system in the Takaka Valley (Mueller 1991).

Faults and fold structures play an important role in constraining recharge and discharge boundaries. They can also act as potential barriers, or avenues, for inter-aquifer and intra-aquifer groundwater movement (LeGrand 1983).

The Pikikiruna Fault is an important recharge zone for the limestone aquifer at East Takaka. The East Takaka Fault system is assumed in this thesis to play a role in the transfer of water between the karst aquifers that are otherwise confined. The faults will act as barriers to flow, or as avenues for groundwater movement, depending on the nature of the fault zone material. If the zone is clay-plugged and gouge-dominated the former will be the case. There is no existing subsurface geological evidence for either condition. Overall, the existence of the East Takaka Fault system underlying the Takaka River complicates the understanding of both inter-aquifer (between Arthur Marble and Takaka Limestone) and intra-aquifer (within separate aquifers) groundwater flow. Lack of any borehole control or water level measurements in the East Takaka Fault zone hinders detailed investigation.

2.5.3 Hydrogeologic implications of karst geomorphology

The Takaka River is an important recharge source for the main karst aquifer. The gravel cover is minimal (assumed to be of the order of 10-15 m) and overlies karstified marble or limestone; its presence facilitates concentrated input via river sinks. The amount of river flow loss depends on several factors: the capacity of river sinks, the gross input from the Upper Takaka River, and various other hydrologic parameters which are dealt with in greater detail in Chapter Three.

Due to their scattered nature and limited abundance, dolines in the Takaka Valley play only a minimal role in the recharge of the main karstic aquifer. They are, however, important in providing a surface expression of probable concentrated groundwater flow paths. As they have a direct connection (when permeable) to the aquifer, and provide for semi-concentrated inputs (from rainfall events), the preservation of the quality of these sinks is an important water quality management issue.

2.6 AQUIFER SYSTEMS OF THE TAKAKA VALLEY

2.6.1 Aquifer description and nomenclature

As previously outlined in section 1.4, the Takaka Valley aquifer system is comprised of three water bearing formations, namely Ordovician Arthur Marble, Oligocene Takaka Limestone, and Quaternary Gravels. There are two principal aquitards (confining layers), namely the Motupipi Coal Measures and the Tarakohe Mudstone. Stratigraphical, lithological, and hydrological information is given in Figure 2.1.

Recognition of three distinct aquifers in the Takaka Valley (Williams 1977, Williams and Stewart 1981) led to the first comprehensive attempt at nomenclature for the Takaka Valley aquifer system by Mueller (1987, 1992). The nomenclature proposed here follows in part Mueller's 1992 system.

The principal aquifer in the Takaka Valley aquifer system is herein referred to as the Waikoropupu Arthur Marble Aquifer, or WAM aquifer. This is an amalgamation of its two previous names, which were Arthur Marble Aquifer (Mueller 1987) and Waikoropupu Aquifer (Mueller 1992). In this renaming, the principal water bearing formation of Ordovician Arthur Marble and the primary discharge site of Waikoropupu Springs are recognised.

The Takaka Limestone Aquifer, which had formerly been subdivded with the parts named the Motupipi and Central Takaka aquifers, is redefined. It is renamed the East Takaka-Motupipi Limestone Aquifer, or ETML Aquifer. Subdivision into sub-aquifers is discussed in section 4.3.1.

The nomenclature of the Quaternary Gravel aquifers follows that proposed by Mueller (1992), wherein numerous aquifers of variable extent were named after their localities, viz. East Takaka Gravel Aquifer, Takaka Gravel Aquifer, Kotinga Gravel Aquifer, Uruwhenua Gravel Aquifer, and Hamama Gravel Aquifer. The Takaka Gravel Aquifer is renamed the Takaka Township Gravel Aquifer, or TTG Aquifer. It, together with the East Takaka Gravel Aquifer, or ETG Aquifer, provides the focus for discussions on gravel aquifers presented in Chapter Four.

2.6.2 Delineation and nature of aquifer boundaries

The delineation of an aquifer entails the determination of both the vertical and the areal extent of the water bearing lithologies. Carbonate rock terranes are not always entirely water bearing; some parts are either impermeable or above the zone of saturation (White 1988). Estimation of aquifer extent is critical to calculations of total volume and aquifer thickness, and hence to the derivation of physical aquifer characteristics.

The nature of aquifer boundaries, both in the vertical and horizontal sense, defines whether the aquifer is confined or unconfined (Fetter 1994). The controls and influencing factors in delineation and boundary description include geology, geomorphology, climate, and biological factors (Ford and Williams 1989). These contribute variably to the aquifer location and to the quantities of recharge and discharge of an aquifer system.

2.6.2.1 Waikoropupu Arthur Marble Aquifer

The largest aquifer in the Takaka Valley aquifer system is the Waikoropupu Arthur Marble Aquifer (WAM), covering an estimated minimum area of 70 km^2 (Mueller 1991). This area comprises an unconfined section of 45 km^2 and a section of 25 km^2 which is confined by the Motupipi Coal Measures (Figure 2.10).

The unconfined section of the WAM Aquifer is bounded to the east and west by the Pikikiruna and Tasman Ranges respectively. The northern boundary of the unconfined section is transitional, located near Gorge Creek (Figure 2.10). Within the unconfined section of the WAM Aquifer, Takaka Limestone unconformably overlies Ordovician Arthur Marble, and these two units are hydraulically connected (Mueller 1992).

The confined section of the WAM Aquifer is flanked by the eastern and western ranges, and has a minimum area of 25 km^2 (Mueller 1992). The existence of a submarine northern boundary of the confined section was assumed (Mueller 1987, 1991, 1992, Williams 1977, 1992), however its position has not been located. The total extent of the confined section of the WAM aquifer is therefore unknown. The above figure of 25 km^2 is taken to represent the aquifer area south of Waikoropupu Springs (Figure 2.10).

The horizontal boundaries of the total WAM Aquifer were arbitrarily set at the 100 m contour line by Mueller (1991); his delineation is recognised in this study as artificial and restrictive. Horizontal boundaries of karst aquifers can deviate significantly both temporally and spatially. Lateral phreatic boundary deviation, noted by Ford and Williams (1989), provides evidence for their dynamic nature. Unlike their counterparts in conventional hydrologic situations, karstic boundaries are unlikely to coincide with

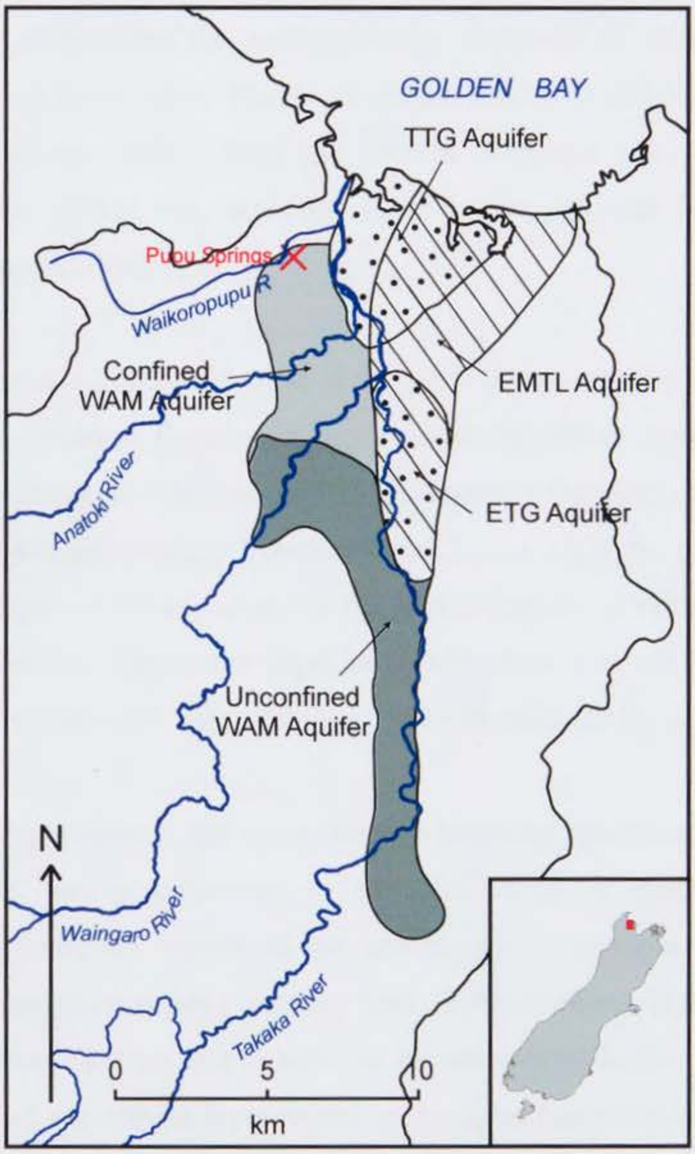


Figure 2.10. Takaka Valley aquifer system

topographic divides (Ford and Williams 1989). Inevitably, the figures presented for the horizontal extent of the WAM Aquifer will be estimates. Any results involving these figures must be interpreted accordingly.

The vertical extent of the WAM Aquifer, being determined by the depth of karstification, may differ from the total lithologic thickness of Ordovician Arthur Marble. Estimates of total Arthur Marble thickness have included 500+ m (Mueller 1991), 1000 m (Williams, 1977, 1992), and 1500 m (Coleman 1981). The thickness measure in Coleman (1981) was, however, based on an apparent full stratigraphic section in the Wangapeka Valley.

Karst aquifer thickness is a direct function of the depth of penetrable fissure, and under immense lithostatic pressures fissuring at depth can be hampered (Ford and Williams 1989). The lower vertical boundary of the WAM Aquifer is therefore constricted to the level where no significant porosity has developed. i.e. to the base of karstification. Likely minimum depth of karstification for the WAM Aquifer is estimated at 100 m (Evidence WWD - 6011). Maximum depth of karstification is in the order of several hundred metres (Williams 1977, 1992, Mueller 1992); Mueller (1991) suggested 360 m.

The nature of the upper contact and upper vertical boundary conditions for the WAM Aquifer is variable, and is controlled by the distribution of overlying confining sediments. In the confined section of the aquifer, the impervious Motupipi Coal Measures act as an upper boundary confining layer. Total thickness is unknown, and is likely to vary considerably from east to west. In the unconfined section south of Gorge Creek, the absence of a confining layer results in the upper boundary being determined by the water table (Figure 2.10). Within this section there is hydraulic connection with Takaka Limestone, hence it is feasible that the fluctuating water table may at times be contained either within Takaka Limestone or within the overlying gravels.

Estimates of the potential cave volume of the WAM Aquifer, based on an approximate areal extent of 70 km^2, have been presented by Mueller (1987, 1992) and Williams (1977, 1992), with figures ranging from 1.5 km^3 to 3 km^3. These figures indicate the vast storage capacity of the aquifer.

2.6.2.2 East Takaka-Motupipi Limestone Aquifer

The East Takaka-Motupipi Limestone Aquifer (ETML) covers an estimated onshore area of 43 km^2 (Figure 2.10). Mueller (1991) considered the limestone aquifer to extend south to Gorge Creek and north to an assumed submarine boundary of unknown position. He estimated total aquifer extent at 35 km^2. In this thesis alternative boundaries are suggested (Figure 2.10), and Mueller's figure of 35 km^2 has been revised.

Due to the structurally complex setting, it is likely that the ETML Aquifer represents a number of isolated to semi-isolated sub-aquifers. Preliminary subdivision is presented in Figure 2.10, on the basis of existing structural mapping (Grindley 1971, Judd 1989). Three sub-aquifers can be envisaged, namely, the East Takaka, Central Takaka-Motupipi, and the Clifton sub-aquifer (which lies to the northeast of the catchment area investigated in this thesis). Discussion of sub-aquifers is presented in Chapter Four.

The eastern boundary of the ETML Aquifer is dictated by the Pikikiruna Fault; this coincides with the designated recharge boundary. Grapes (1994) assumed that the western boundary was marked by the East Takaka Fault system. It is more likely, however, that this western boundary is determined by the lithologic extent of Takaka Limestone. There is limited drillhole data, and accurate assessment of Takaka Limestone distribution is not available. The estimation of the western extent of the ETML Aquifer is shown in Figure 2.10.

As with the WAM Aquifer, the northern boundary of the ETML Aquifer represents a discharge zone. Mueller (1991) assumes the boundary to be submarine, but discharge vents have yet to be located. The southern extent of the ETML Aquifer is transitional, and is located between the limestone incorporated in ETML and the limestone incorporated in the unconfined section of WAM south of Gorge Creek.

As with the WAM Aquifer, the depth of karstification controls the vertical extent of the ETML Aquifer, dictating its lower boundary. Minimum depths are estimated at 20 m (evidence WWD-6422), while maximum depth of karstification is estimated at 60+ m. In certain areas the latter figure would account for the entire thickness of Takaka Limestone (which varies in thickness from 4-62 m, Appendix A-II). If this is the case the lower boundary is dictated by the underlying impervious Motupipi Coal Measures. The upper boundary is determined by the presence of confining Tarakohe Mudstone. Its known thickness ranges from 0-114 m (Appendix A-II).The presence of Tarakohe Mudstone confines the ETML Aquifer. Where Tarakohe Mudstone is not present the ETML Aquifer is unconfined.

2.6.2.3 Quaternary Gravel Aquifers

Quaternary gravel and sand deposits cover most of the Takaka Valley from Upper Takaka to the sea (Stewart and Williams 1981). The major water bearing gravels are Holocene, and can be subdivided into manageable zones according to their location. Of primary interest are the features associated with the East Takaka and the Takaka Township Quaternary Gravel Aquifers, which cover areas of 10 km^2 and 20 km^2 respectively.

While Quaternary gravel deposits are spatially extensive, they are relatively thin; typical gravel thicknesses of East Takaka well logs range from 5.4 m (WWD-6811) to 13 m (WWD-6824). The average vertical extent of the East Takaka Gravel Aquifer (ETG) is 9.0 m (Appendix A-II). The vertical extent of the Takaka Township Gravel Aquifer (TTG) is variable, ranging from 11.0 m (WWD-6301) to 32 m (WWD-6321); the average thickness of TTG gravel deposits is of the order of 15 m.

The western horizontal boundaries of both the ETG and TTG Aquifers are recharge dominated (at least in part), and are determined by the Takaka River. The eastern boundary for the ETG Aquifer is dictated by the Pikikiruna Scarp. The eastern boundary for the TTG Aquifer is determined by the Quaternary terrace on the south east border.

The vertical lower boundary in both aquifers is marked by confining Tarakohe Mudstone, although there may be areas on the periphery (for example at Motupipi, Appendix II) where mudstone is not present. In these instances the Quaternary Gravels will be hydraulically connected with the underlying limestone. The TTG and ETG Aquifers are unconfined, therefore the upper boundary for each is the water table. For both aquifers, areal extents considered in this thesis are shown in Figures 2.11 and 2.12.

2.6.3 Delineation of the Takaka Valley aquifer system

The aquifers in the Takaka Valley can be envisaged as a regional system. The limits of individual aquifers in a system are defined in order to establish hydrogeological controls and to manage groundwater resources. The aquifers could be considered a semi-connected system, with water from the shallow Quaternary gravel aquifers finding its way into the WAM Aquifer. This would occur over a considerable time period. The consideration of any such connections would not negate the importance of defining detailed individual boundary conditions.

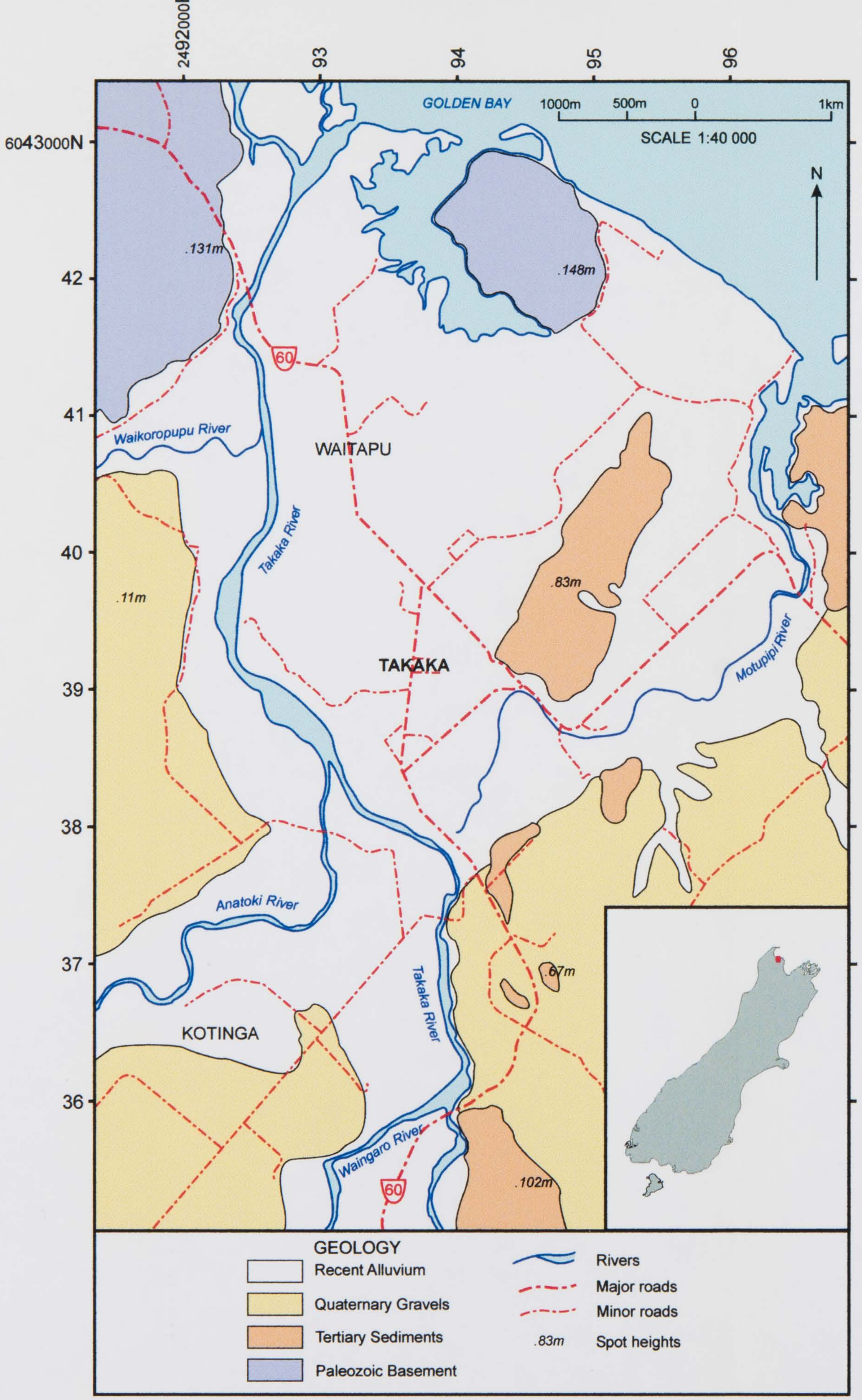


Figure 2.11. Takaka Township Gravel Aquifer study area

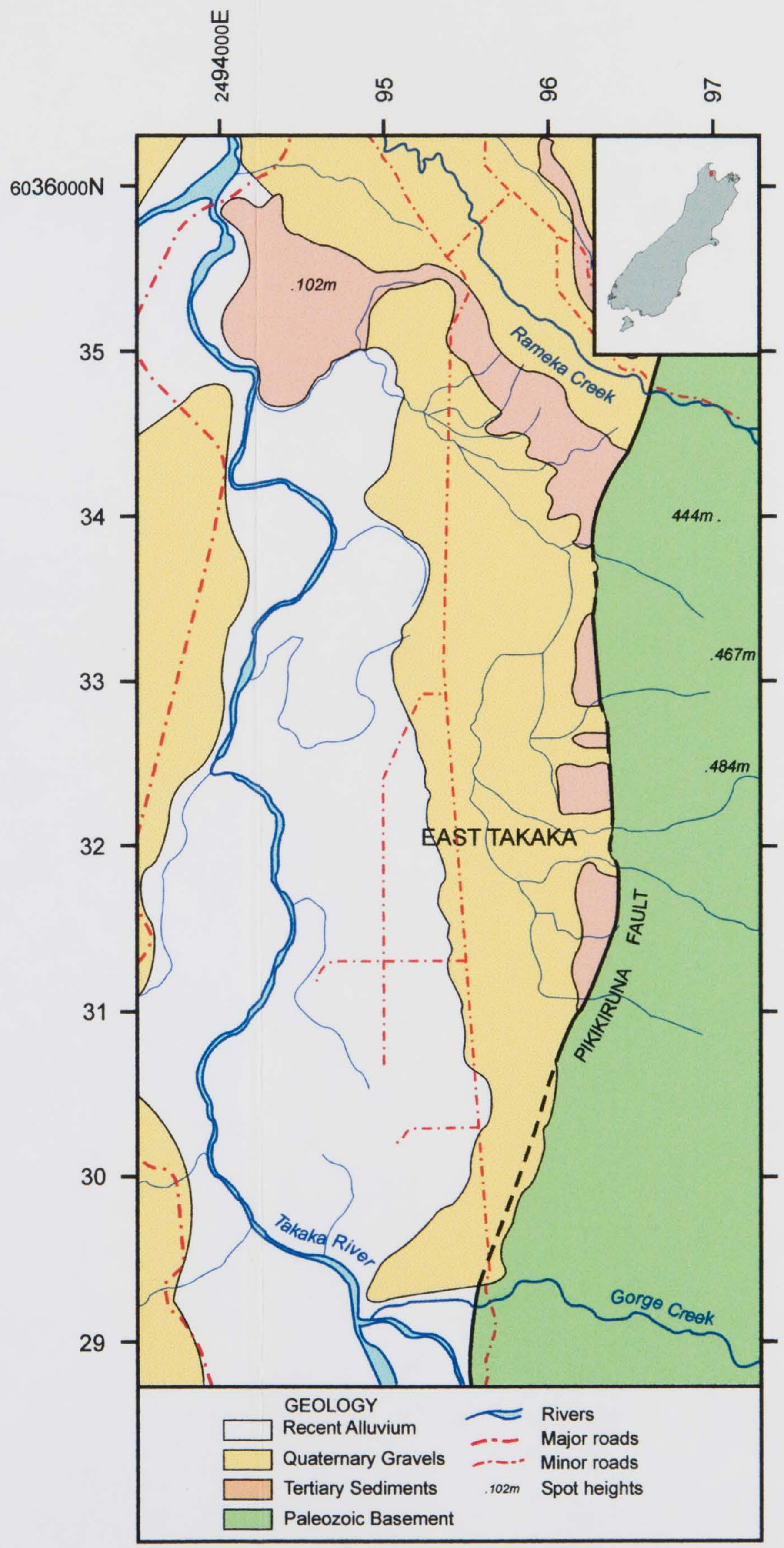


Figure 2.12. East Takaka Gravel Aquifer study area

2.7 SYNTHESIS

Geology, geomorphology, tectonics, and topography delineate and control aquifers in the Takaka Valley.

- The primary water bearing units are Ordovician Arthur Marble, Oligocene Takaka Limestone, and Quaternary Gravels.
- These three comprise the Takaka Valley aquifer system.
- The Pikikiruna Fault and the East Takaka Fault system are the major tectonic structures. They influence aquifer boundary control , recharge, and discharge.
- Karst landforms are not obviously apparent. They include minor sinkholes, and the dry Takaka River, which flows over the unconfined section of the marble aquifer.
- The principal karst aquifer is given the name Waikoropupu Arthur Marble Aquifer, amalgamating its previous two names.
- The minor karst aquifer is given the name the East Takaka-Motupipi Limestone Aquifer, which is an amalgamation of its three sub-aquifers.
- Motupipi Coal Measures and Tarakohe Mudstone are important confining layers for the marble and limestone aquifers respectively. Their extent controls the behaviour of the unconfined vs the confined sections of each.
- Tarakohe Mudstone is the lower boundary for the Quaternary gravel aquifers of East Takaka and Takaka Township.
- The gravel aquifers are part of the spatially extensive gravel deposits flooring the Takaka Valley.

CHAPTER THREE : HYDROGEOLOGY OF THE WAIKOROPUPU ARTHUR MARBLE AQUIFER

3.1 INTRODUCTION

A karst aquifer can be envisaged as an open system (Ford and Williams 1989), where boundaries are defined by catchment limits, and controls are defined by inputs, throughputs, and outputs. The level of information available for aquifer analysis varies. Difficulties arise in the study of karst systems because information on throughput controls (conduit systems, conduit geometry, and flow paths) is often difficult or impossible to obtain. The study of karst aquifers is therefore often confined to evaluation of inputs and outputs. The need to understand recharge sources and discharge sites of an aquifer is integral to resource management and provision of water quantity and quality.

This chapter has been separated into four sections as follows:

- Recharge sources: identification of principal components, description of recharge zones, and quantification (or estimation) of inputs,
- Discharge sites: evaluation of the major springs in the WAM Aquifer (including springs setting, discharge characteristics, and hydrograph analysis), and discussion and reevaluation of models of spring discharge,
- Aquifer fluctuations: assessment of long term and short term fluctuations for the Balls water level recorder (June 1994-January 1998), and
- Synthesis: summary of the above.

This chapter will not examine aquifer throughput. Groundwater flow is broadly directed by regional hydraulic gradients (i.e. towards the coast line). The actual flow routes are controlled by the geologic structure and by the organised patterns of drainage conduits that develop over time (Halihan *et al* 1998). In the WAM Aquifer a lack of hydraulic information and hydrogeologic controls restricts investigation. Models of WAM Aquifer throughput are presented by Stewart and Williams (1981), Ford and Williams (1989), and Williams (1992).

3.2 RECHARGE SOURCES

3.2.1 Methodology adopted

The identification of recharge sources and the understanding of recharge mechanisms for an aquifer leads to better identification of potential contamination risks, and establishes input controls into the aquifer system. The existing literature on recharge analysis of karst aquifer systems is not extensive. It is based either on small scale systems with sinking streams (Greene 1997), or on diffuse recharge regimes where recession curve displacement methods estimate the total recharge (Perez 1997, Padilla *et al.* 1994, Rutledge and Daniel 1994). None of the studies mentioned provide particularly useful information for the study of the WAM Aquifer.

The WAM Aquifer recharge is complicated, in that it receives both diffuse and concentrated inputs, derived both autogenically and allogenically. The area contributing to recharge is approximately 750 km^2.

Procedures adopted in this study are based on a water balance approach, and have the following objectives:

- to identify and define the recharge sources,
- to evaluate and analyse the recharge sources, and estimate or quantify the input of the primary sources, and
- to emphasise data limitations.

Previous attempts at recharge analysis for the WAM aquifer have been made by Mueller (1987, 1992) and Stewart and Williams (1981). Mueller (1992) adopted a water balance approach, giving a useful analysis of river sink contribution. His analysis of other components of flow, however, was based on unsubstantiated estimates. He claimed the existence of an 8-9 m^3s^{-1} component of discharge issuing from submarine springs. Stewart and Williams (1981) used isotope analysis to characterise the recharge of WAM and other aquifers in the Takaka Valley. They confirmed that the Takaka River is an important source of recharge for WAM, contributing an estimated 50 %.

The principal assumptions in the water balance approach in this study are as follows:

- The five recharge sources (outlined in section 3.2.2) are the major contributors to the WAM Aquifer,
- No additional contribution from neighbouring catchments occurs, and
- The Waikoropupu Springs system represents the primary discharge zone of the WAM Aquifer. Minor discharges at Spring Brook and Spittals Springs are assumed negligible for the purposes of recharge balance.

3.2.2 Recharge styles and classification

Recharge of the WAM Aquifer is complex, and influenced by both autogenic and allogenic components. Autogenic input is derived solely from precipitation falling on karstic rock outcrops (Ford and Williams 1989). Allogenic input involves water which has fallen on non-karstic neighbouring or overlying rocks, and has then drained into a karst aquifer (White 1988). Autogenic recharge is viewed as the simplest case (Ford and Williams 1989), and is often regarded as being predominantly diffuse (Gunn 1983). In comparison, allogenic recharge is considered more complex, and is usually associated with concentrated linear or point inputs (Ford and Williams 1989, Gunn 1983). The style of recharge (autogenic/allogenic, and diffuse/concentrated) affects the water chemistry, and physical characteristics of an aquifer.

Five principal recharge sources for the WAM Aquifer have been identified (Figure 3.1), and are detailed below:

1. Concentrated allogenic recharge represents runoff generated from non karstic rocks in the Upper Takaka Valley, and in parts of the Central Takaka Valley and Waingaro sub-catchments. This runoff is lost underground via river sinks or stream sinks.
2. Diffuse autogenic recharge is recharge derived from precipitation falling on Ordovician Arthur Marble, and is mainly confined to the karstic plateau (Canaan Downs, and Takaka Hill), Pikikiruna Range, and along the foothills of the Western Ranges.
3. Diffuse allogenic recharge infiltrates the permeable Quaternary gravel deposits and perforated Takaka Limestone in the unconfined section of the WAM Aquifer.

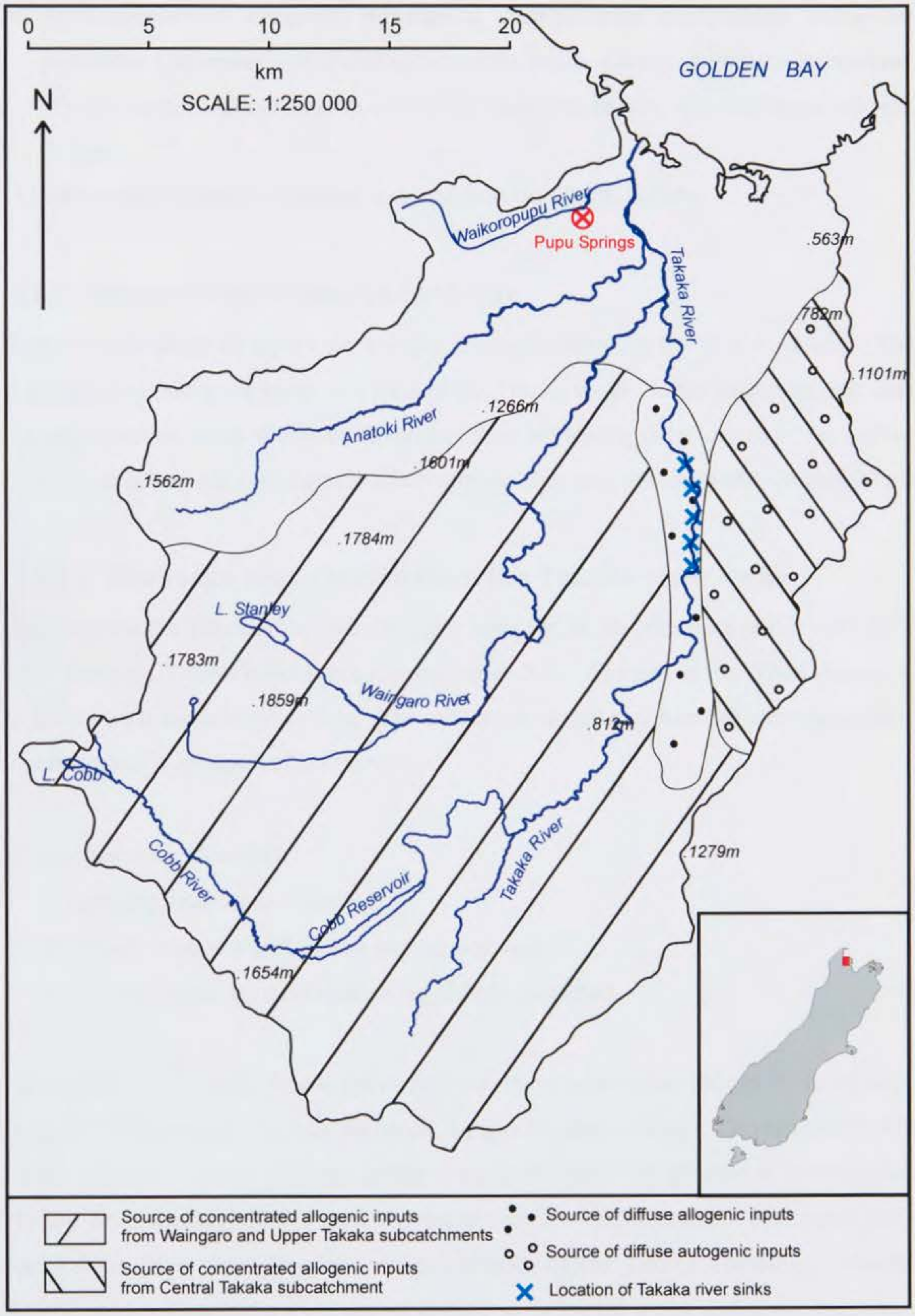


Figure 3.1. Sources and areas of recharge contribution to the WAM Aquifer

4. Semi-concentrated autogenic recharge is derived from precipitation falling on permeable Quaternary gravel and soil deposits which directly overlie the unconfined WAM Aquifer. Concentration occurs via funneling of rain into developed solution dolines.
5. Inter-aquifer leakage is potential recharge from the ETML Aquifer.

3.2.3 Concentrated allogenic recharge

Concentrated allogenic inputs are a major recharge source for the WAM Aquifer. The principal river sinks are found in a zone of the Takaka River. Other important sink sites include a section of the Waingaro River, and there are stream sinks located in the Eastern and Western foothills, coincident to where streams flow over Arthur Marble (Figure 2.1).

3.2.3.1 Recharge contribution from the Takaka river sinks

Recharge via the Takaka river sinks is highly complex, as the behaviour of the water table underlying the Takaka River is not known (Figure 3.2). This part of the WAM Aquifer is a hybrid karst and alluvial system. The evaluation of recharge uses the existing gauging database, and is approached as follows:

- loss zones are identified,
- the gauging database is evaluated,
- the observed pattern of flow loss is described, and
- the recharge input via the Takaka river sinks is quantified.

Williams (1977) was the first to prove the connection between the Takaka River recharge zone and Waikoropupu Springs discharge, using pulse train analysis. This connection had been suspected by many previous writers (Park 1890, Bell 1908, Henderson 1928, Rapier 1975). From the early 1980's several series of river flow measurements were made along the Takaka River from Harwoods to downstream of the Takaka Township. Mueller (1992) used one particular gauging run in 1991 to define the major and minor loss zones of the Takaka River. He estimated the average river loss at approximately 11 m^3s^{-1}, and the maximum recharge loss at 15 m^3s^{-1}.

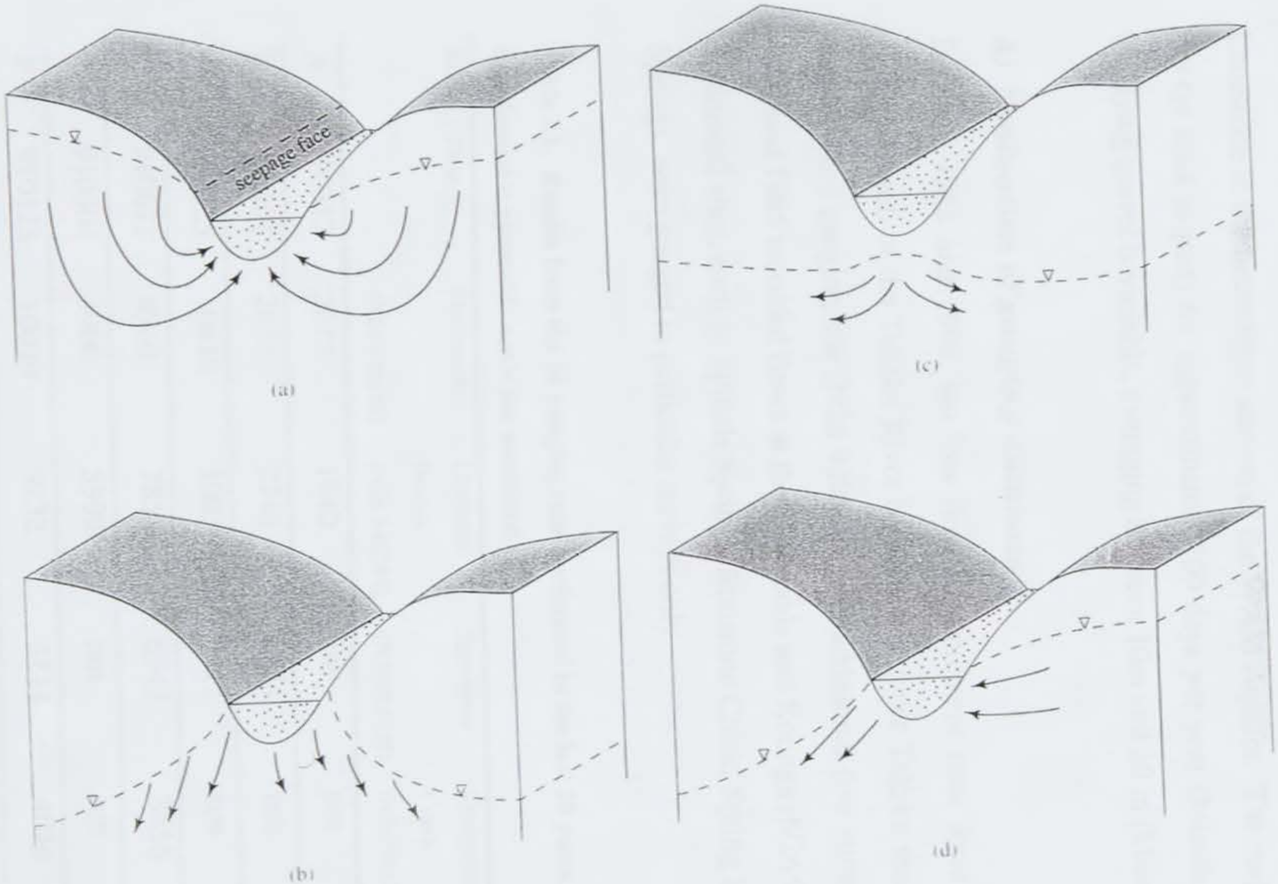


Figure 3.2. Possible Takaka River-aquifer relations

(a) gaining stream receiving water from groundwater flow,
(b) losing stream connected to water table,
(c) losing stream perched above the water table,
(d) flow through stream (From Dingman 1993)

The major recharge reach starts downstream of Lindsays Bridge (N26 952244) and extends approximately 8 km to upstream of Spring Brook (N26 942310). A minor loss zone exists between the Harwoods recorder (N26 930196) and the Waitui Stream-Takaka River confluence (N26 950210). Locations of both loss zones are geologically controlled, and coincide with the distribution of karstifed Ordovician Arthur Marble and Takaka Limestone in the unconfined section of the WAM Aquifer. The major recharge reach runs dry (at least in part) for approximately 100 days per year (Mueller 1992). Coverage of overlying gravel is variable, averaging between 10m and 20 m (Mueller 1992).

A) Evaluation of gauging database

Between 1988 and 1998, ten low flow measurement runs were carried out along the recharge reach of the Takaka River between the upper Takaka recorder at Harwoods and Paynes Ford gauging site (N26 939359). An additional five surveys conducted between 1973 and 1985 recorded flows at the Harwoods and Kotinga (N26 939372) recorders only. Additional sites, such as Spittals Springs, Ironstone Creek, Spring Brook, and East Takaka Springs, were gauged in particular surveys only.

Table 3.1. Results from the 10 gauging runs performed in the last 10 years. Flow is given in l/s. Date time format is yymmdd. nm = not measured

Run	Date	Harwoods (N26 930195)	Lindsays Bridge (N26 946244)	Sparrows (N26952250)	Craigieburn Creek (N26 953274)	Paynes Ford (N26 940358)
A	970317	2675	1840	nm	nm	347
B	960401	2655	2348	1474	nm	952
C	960125	10810	10036	9813	nm	8682
D	910621	8969	7855	6942	3436	269
E	910304	5900	5999	nm	nm	520
F	910123	10030	9232	8114	4036	830
G	900308	1751	nm	nm	nm	257
H	890426	2040	nm	nm	nm	577
I	880419	9406	8598	nm	3615	2174
J	881122	nm	4683	nm	378	nm

All gauging details are presented in Appendix C-II. The results and locations of gauging runs used in this section are shown in Table 3.1 and Figure 3.3.

Inputs into the Upper Takaka River (measured at Harwoods) are made up of variable proportions of Takaka River flow, artificial Cobb power station inputs, and residual Cobb River flow. Hydrographs are examined for the seven days prior to gauging in order to ensure the relatively stability of river flow.

Results from Table 3.1 for selected runs (A-F) are displayed in Figures 3.4a and 3.4b. All surveys highlight the major loss reach downstream of Lindsays Bridge, with only minor losses apparent between the Harwoods recorder and Lindsays Bridge. Gauging run F is the most comprehensive, involving nine sites between the Harwoods recorder and Paynes Ford in addition to those shown in Table 3.1.

In gauging runs A, D, E, and F the places where river flow ceased are noted. These occur upstream of Craigieburn Creek, upstream of Stoney Creek, downstream of Craigieburn Creek, and downstream of Stoney Creek respectively (Figure 3.4b).

The downstream boundary of the Takaka River recharge reach is likely to be transitional, located upstream of the Spring Brook-Takaka River confluence. The river channel downstream of the boundary is assumed to be underlain by confining Tertiary sediments, as evidenced by the Motupipi Coal Measures cropping out approximately 1 km away. Minor losses that are noted downstream of the Spring Brook-Takaka River confluence are assumed to contribute to the surrounding gravels or travel as interflow through the channel gravel. They do not contribute to the WAM Aquifer.

Paynes Ford gauging site, located upstream from the Waingaro River-Takaka River confluence, is the final site of interest in the WAM Aquifer recharge investigations. The measured flow component at this site is comprised of residual flow from the Takaka River (including Spring Brook and East Takaka Springs discharge), and contributing quantities of interflow (from either Takaka River gravels or Waingaro River gravels, typically of the order of 0.5 - 1.5 m^3s^{-1}) (Rapier 1975). The conspicuous result from gauging run C, which measures an appreciably higher component of outflow at Paynes Ford (of the order of

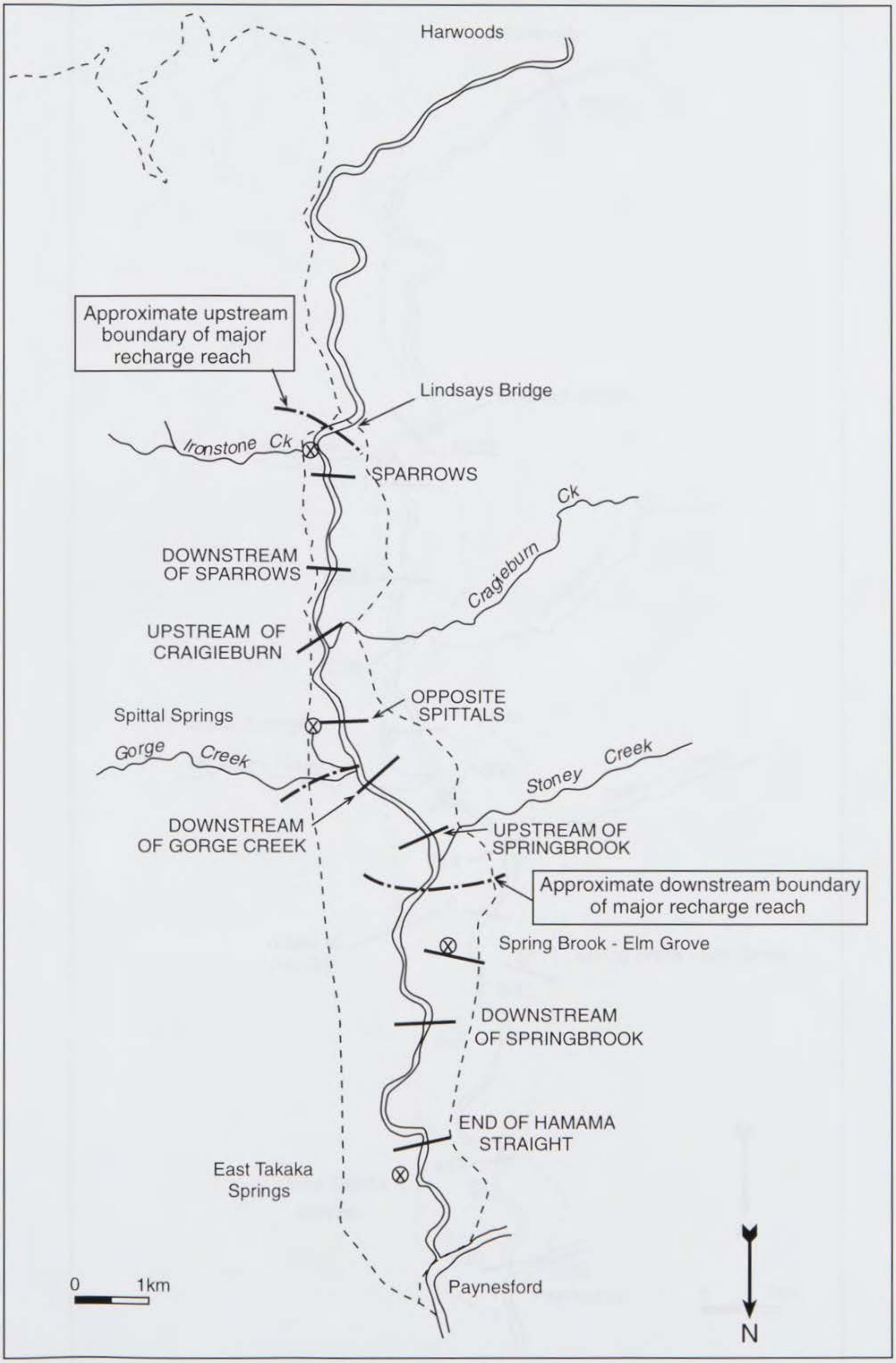


Figure 3.3: Location of Takaka River gauging sites

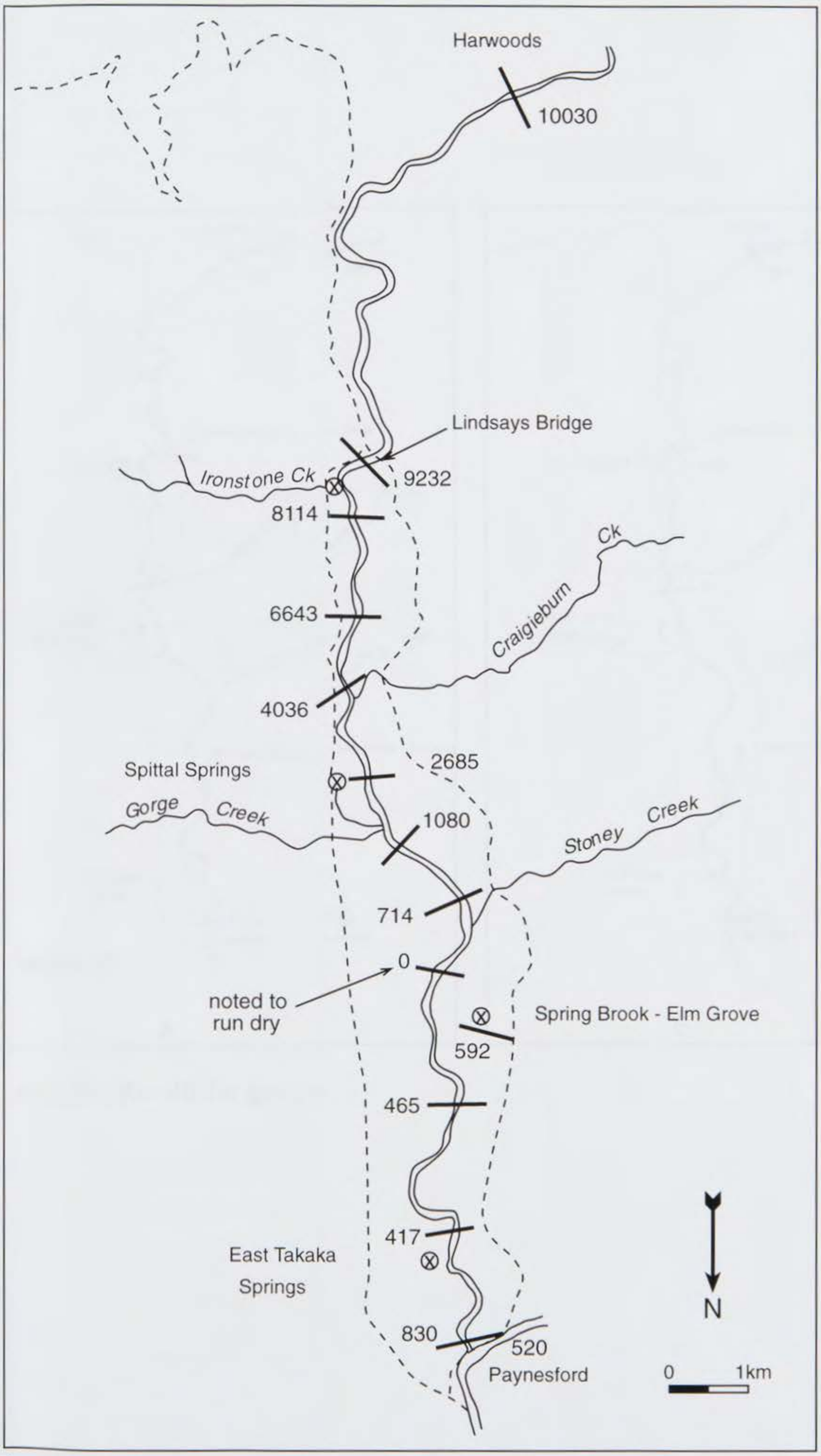


Figure 3.4a: Results for gauging run F along the Takaka River recharge reach. Flow is given in litres/sec.

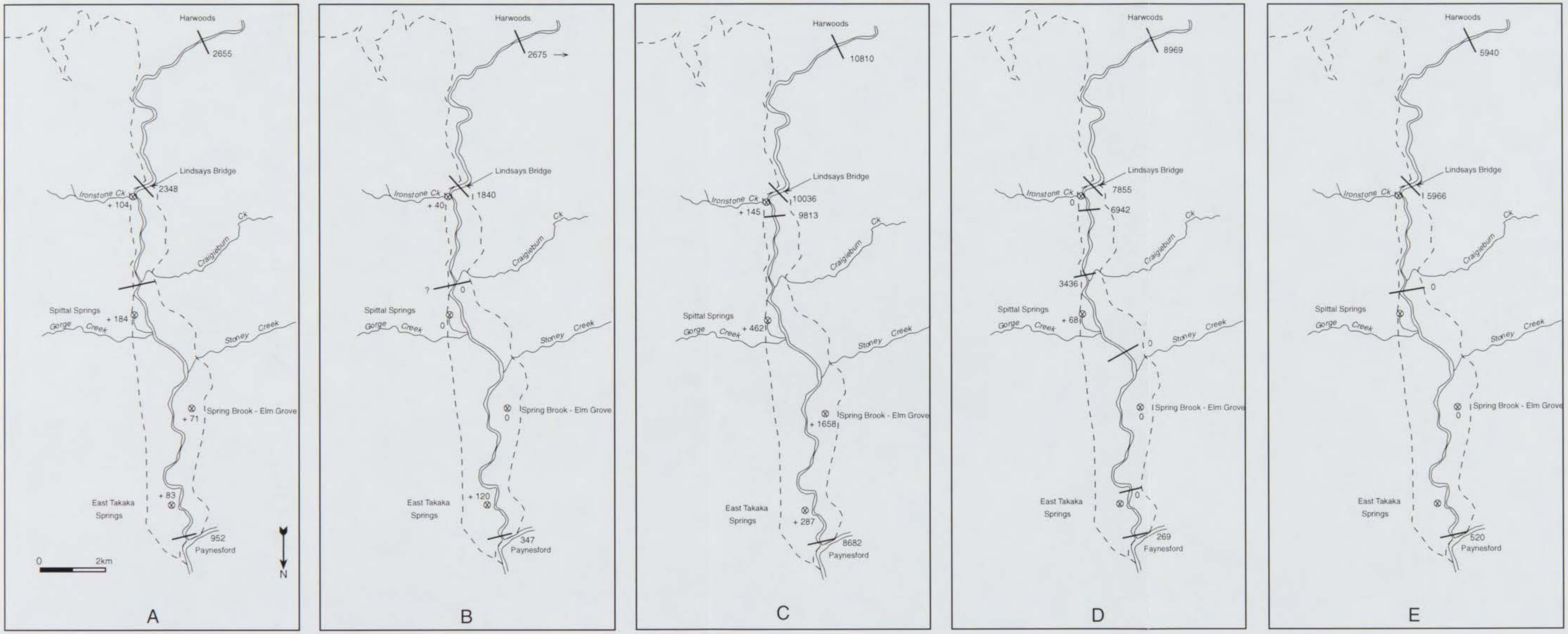


Figure 3.4b: Results for gauging runs A - E along the Takaka River recharge reach. Flow is given in litres/sec.

8682 l/s), is thought to be a result of increased contribution from gravel water. Since gauging runs C and D involve comparable inputs, antecedent hydrologic and rainfall conditions for them are compared. A large flood was recorded 10 days prior to sampling in run C, with peak flows at Harwoods of approximately 220000 l/s, and peak flows at Waingaro River of approximately 440000 l/s. Mean flows for the 10 day period prior to gauging run D are of the order of 4000-6000 l/s.

B) Description and significance of river loss

The pattern of flow loss from the Takaka River between Harwoods and downstream of Stoney Creek (in gauging run F) is one of gradual seepage as opposed to point loss. This can be clearly seen in Figure 3.5a. Flow is relatively constant between Harwoods and Lindsays Bridge, then decreases steadily between Lindsays Bridge and the last gauging site, upstream of Stoney Creek.

In contrast, an extreme example of a plot expected from point recharge in a karst river sink system is shown in Figure 3.5b. This plot displays prominent steps, which clearly identify the definite and distinct sink points. Sink zones associated with point loss could still exist within the karst underlying the Takaka River, but the presence and thickness of overlying gravels (10 -20 m) makes gradual seepage dominant. The overlying gravels act as a consistent filter and render the underlying sink zones (into the WAM Aquifer) immune to plugging by debris and sediment. During low flow periods in the summers of 1997 and 1998 no surface expression of sink points were observed, although previously these were claimed to have been identified (Mueller 1987, 1992).

Upstream and downstream recharge reach boundaries are indicated on Figure 3.5a. This flow regime (Fig 3.5a) is assumed to be representative of the Takaka River sink contribution to the WAM Aquifer. The maximum sink capacity is estimated to be of the order of 10000 l/s. This estimate is obtained by translating the trend line representing flow loss downstream of Lindsays Bridge along the x-axis to the point where the downstream recharge reach boundary is located (dashed line). This line is then extrapolated back to the y-axis in the manner shown (dotted line). The y-intercept represents the maximum flow

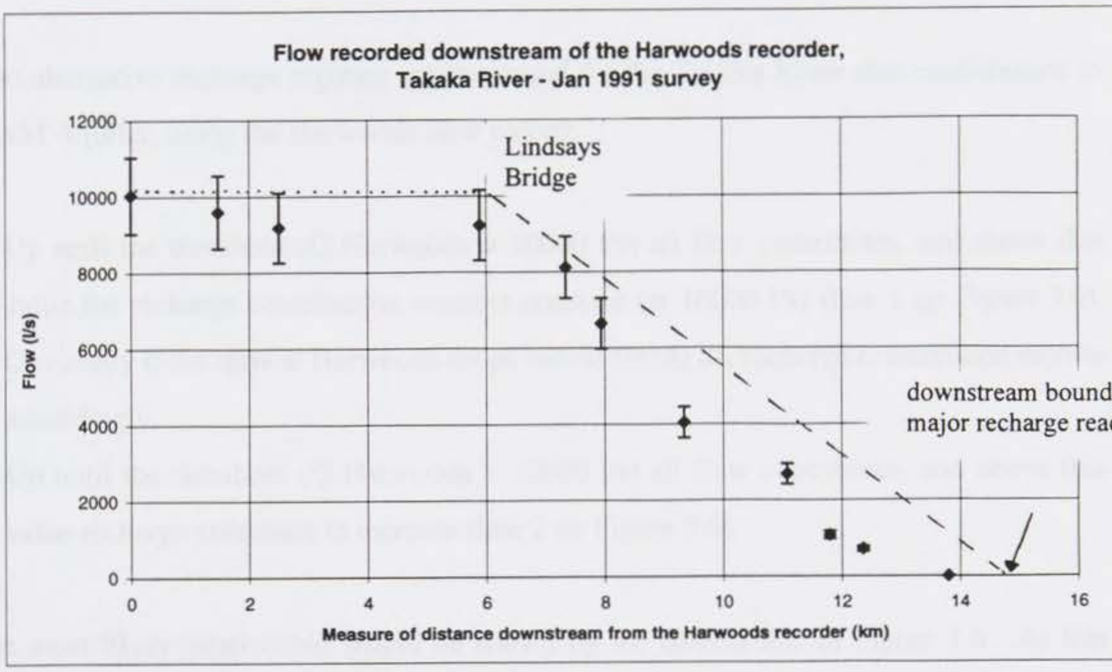


Figure 3.5a. Pattern of flow recorded downstream of the Harwoods recorder (for gauging run F)

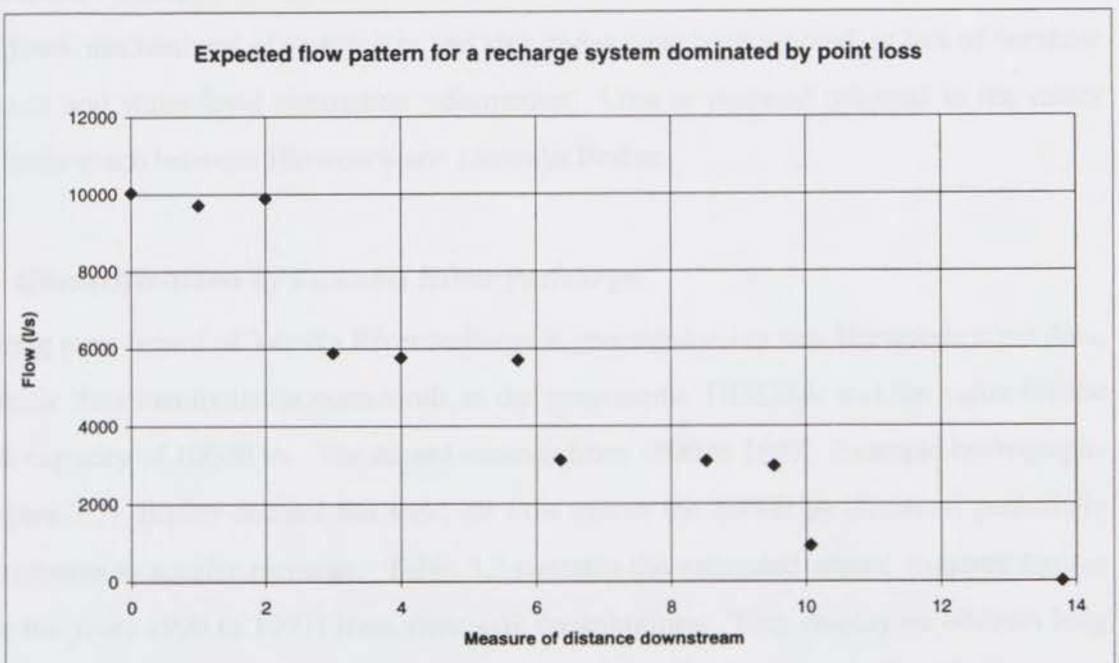


Figure 3.5b. Example river flow plot expected from a system that is dominanted by point recharge

(at Lindsays Bridge) expected to contribute to the sink system. Flow above this figure is assumed to continue downstream.

Two alternative recharge regimes are envisaged for the Takaka River sink contribution to WAM Aquifer, using the Harwoods flow record:

1. Up until the threshold (Q Harwoods = 10000 l/s) all flow contributes, and above this value the recharge contribution remains constant (at 10000 l/s) (line 1 on Figure 3.6). Obviously if the flow at Harwoods drops below 10000 l/s, recharge contribution adjusts accordingly.
2. Up until the threshold (Q Harwoods = 10000 l/s) all flow contributes, and above this value recharge continues to increase (line 2 on Figure 3.6).

The most likely relationship would be shown by the dashed line in Figure 3.6. As this relationship is unable to be physically assessed, for the purposes of river recharge quantification the recharge regime represented by line 1 (Figure 3.6) has been adopted. Maximum recharge is assumed constant and set at 10000-11000 l/s. The inherent feedback mechanisms of sink points and sink zones have been ignored, in lieu of borehole control and water level fluctuation information. Loss is assumed minimal in the minor recharge reach between Harwoods and Lindsays Bridge.

C) Quantification of Takaka River recharge

A long term record of Takaka River recharge is generated using raw Harwoods input data, specific data manipulation commands in the programme TIDEDA, and the value for the sink capacity of 10000 l/s. The record extends from 1990 to 1997. Example hydrographs (Figure 3.7) display distinct flat tops; all flow below the 10000 l/s threshold potentially contributes to aquifer recharge. Table 3.2 contains the estimated annual recharge figures (for the years 1990 to 1997) from river sink contributions. They display no obvious long term recharge trend, and range between 281×10^6 $m^3yr^{-1}$and 207×10^6 m^3yr^{-1} . The variations reflect the differences between dry and wet years (e.g. in 1997 recharge is low, and coincides with a particularly dry year).

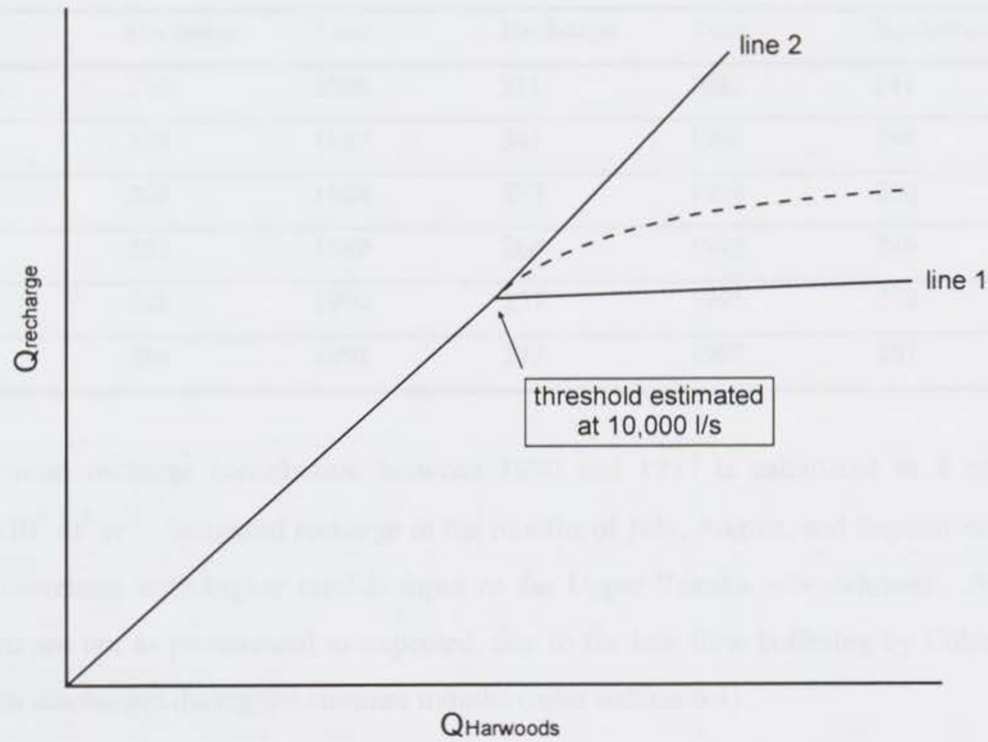


Figure 3.6. Relationship of recharge and inflow at Harwoods

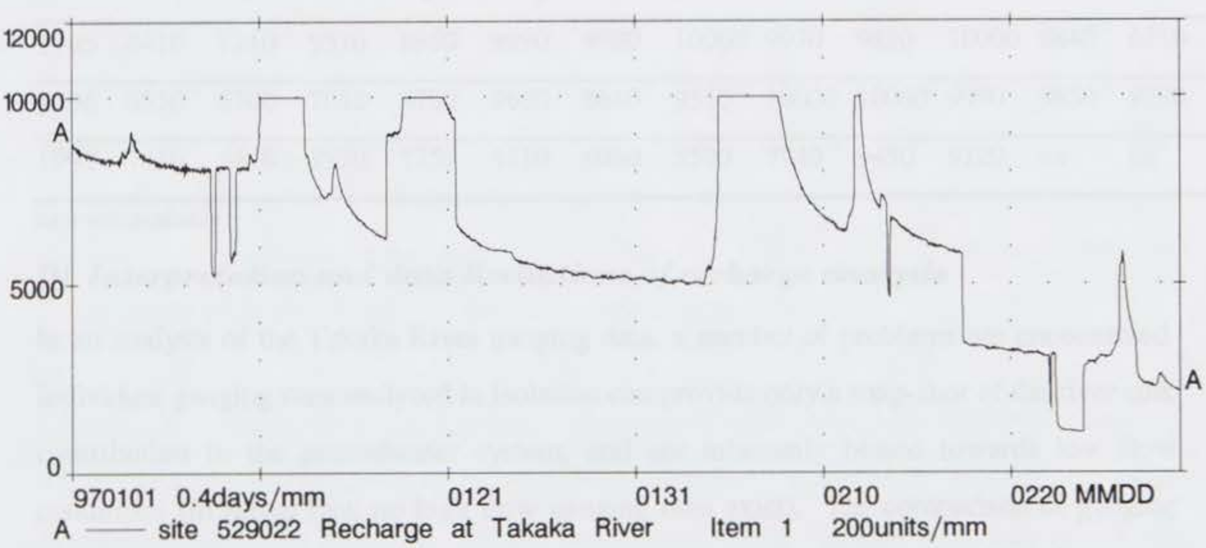


Figure 3.7. An example hydrograph (for January to June) of recharge contribution from the Takaka River

Table 3.2. Recharge (expressed as $m^3yr^{-1} \times 10^6$) from the Takaka River. This is derived from generated river loss data set, which assumes constant recharge above Harwoods input of 10000 l/s.

Year	Recharge	Year	Recharge	Year	Recharge
1980	276	1986	281	1992	241
1981	239	1987	241	1993	246
1982	208	1988	273	1994	260
1983	252	1989	268	1995	276
1984	248	1990	237	1996	278
1985	264	1991	247	1997	207

The mean recharge contribution between 1990 and 1997 is calculated as 8 m^3s^{-1}, or 251×10^6 m^3 yr^{-1}. Increased recharge in the months of July, August, and September (Table 3.3) correlates with higher rainfall input in the Upper Takaka subcatchment. Seasonal effects are not as pronounced as expected, due to the low flow buffering by Cobb power station discharges during the summer months (refer section 6.4).

Table 3.3. Mean monthly recharge from Takaka river sinks (l/s), estimated using generated river loss site. Value of 10000 l/s indicates maximum recharge.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1995	4410	7210	9510	8950	9890	9980	10000	9970	9880	10000	8840	6510
1996	6550	6700	7010	8790	9680	8640	9510	10000	10000	9990	9850	9290
1997	7450	5410	2930	5750	6110	6080	5560	7940	9450	9120	na	na

na = not available

D) Interpretation and data limitations of recharge analysis

In an analysis of the Takaka River gauging data, a number of problems are encountered. Individual gauging runs analysed in isolation can provide only a snap-shot of the river sink contribution to the groundwater system, and are inherently biased towards low flow conditions (in actual fact, no high flow gauging runs exist). The comparison of gauging runs, while advantageous, is hampered by the variability and inconsistency of gauging sites. Not all gauging runs measure accurately where the river ceases to flow, and not all runs measure additional inputs, such as Ironstone Creek, East Takaka Springs, and Spring Brook. The most useful results are gleaned from comprehensive survey F (section 3.2.3.1) and in lieu of detailed hydrogeologic and hydraulic information, recharge is assumed to be steady and gauging run F is assumed to be representative.

With increased flow in the Takaka River more water would enter the sink system, and recharge could occur at a rate greater than that with which the system could cope. The capacity of sinks would fluctuate according to storage conditions and antecedent hydrological conditions. To accurately assess fluctuating sink capacity, monitoring of water table fluctuations along the recharge reach would be required. Even with this additional information, water table behaviour would still prove difficult to analyse. The limited and mainly speculative nature of physical information, and the unknown influence of faulting in the Takaka River recharge zone (from the East Takaka Fault system) both hamper investigation. The limited information available on conduit connections and interconnections, and on preferential flow paths, further hinders understanding. To incorporate fluctuating sink capacity, it has been postulated that approximately 10 % of the flow above 10000 l/s contributes to the WAM Aquifer (pers. comm. Smart 1998).

The complex nature of the WAM Aquifer system underlying the Takaka River is exemplified by some erroneous gauging results recorded (at Elm Grove) for the Spring Brook discharge. Elm Grove (located 600 m west of the main river channel, and slightly higher in elevation) recorded flow values of 71 l/s and 592 l/s when the river was dry (gauging runs B and F respectively). On hydraulic considerations alone it is likely that Spring Brook is fed by a separate conduit system, or is a subsystem (offshoot, or link) to the principal drainage arrangement underlying the Takaka River. A more detailed examination of Spring Brook discharge is given is section 3.3.4.

Taking into consideration the limitations outlined above (most importantly, the lack of hydraulic information), the input into the WAM Aquifer system via the Takaka river sinks is estimated at 8-9 m^3s^{-1}. This accounts for some 55 % of the total input into the WAM Aquifer system. The imbalance is assumed to be derived from alternative recharge sources; these are discussed in the following sections.

3.2.3.2 Recharge contribution from the Waingaro river sinks

Geologic interpretation (based on Sheet 8, Grindley 1971) and geomorphologic interpretation (based on aerial photos) confine the recharge reach of the Waingaro River to between downstream of Hanging Rock (M26 889295) and downstream of Savages gauging site (at approximately N26 918340). This reach coincides with a band of Arthur Marble, which is observed cropping out to the south of Hamama Road (Figure 2.1), and which is assumed to underlie recent alluvium and Bainham I and II gravel terraces. An estimate by Mueller (1992) of combined flow loss from the Waingaro and Anatoki Rivers was of the order of 2 m^3s^{-1}.

A) Evaluation of existing gauging database

Between 1988 and 1998, nine gauging runs, incorporating up to seven sites (Figure 3.8), were carried out along the stretch of Waingaro River between Hanging Rock (M26 889296) and the Waingaro River-Takaka River confluence (N26 938360). Of primary interest is the flow regime recorded between sites 1 (Hanging Rock) and 4 (Savages). Flow results for five selected surveys (A-E) are presented in Table 3.4. Figures 3.9 (a-e) clearly track flow losses and gains down the main stem. All gauging details and pertinent site details are presented in Appendix C-II.

Overall, survey D shows the greatest loss (between sites 1 and 4) relative to input at site 1 (15 %). Other surveys record losses between 7 and 10 %. There is no obvious discernible loss variation between gaugings performed under low or moderate flow conditions (Table 3.4). Recorded flows for surveys A, B, and C (between sites 1 and 2 and sites 2 and 3) are inconsistent, with both losses and gains observed. While recharge rates are expected to vary from one location to another as the permeability of covering material varies (Fetter 1994), there is also the possibility of impervious Wangapeka Formation underlying sections of the recharge reach. There is evidence for a complicated relationship between Arthur Marble and the Wangapeka Formation nearby (Grindley 1971). Downstream of site 4, flow losses are assumed to contribute to the surrounding gravels or travel as interflow through the channel gravels.

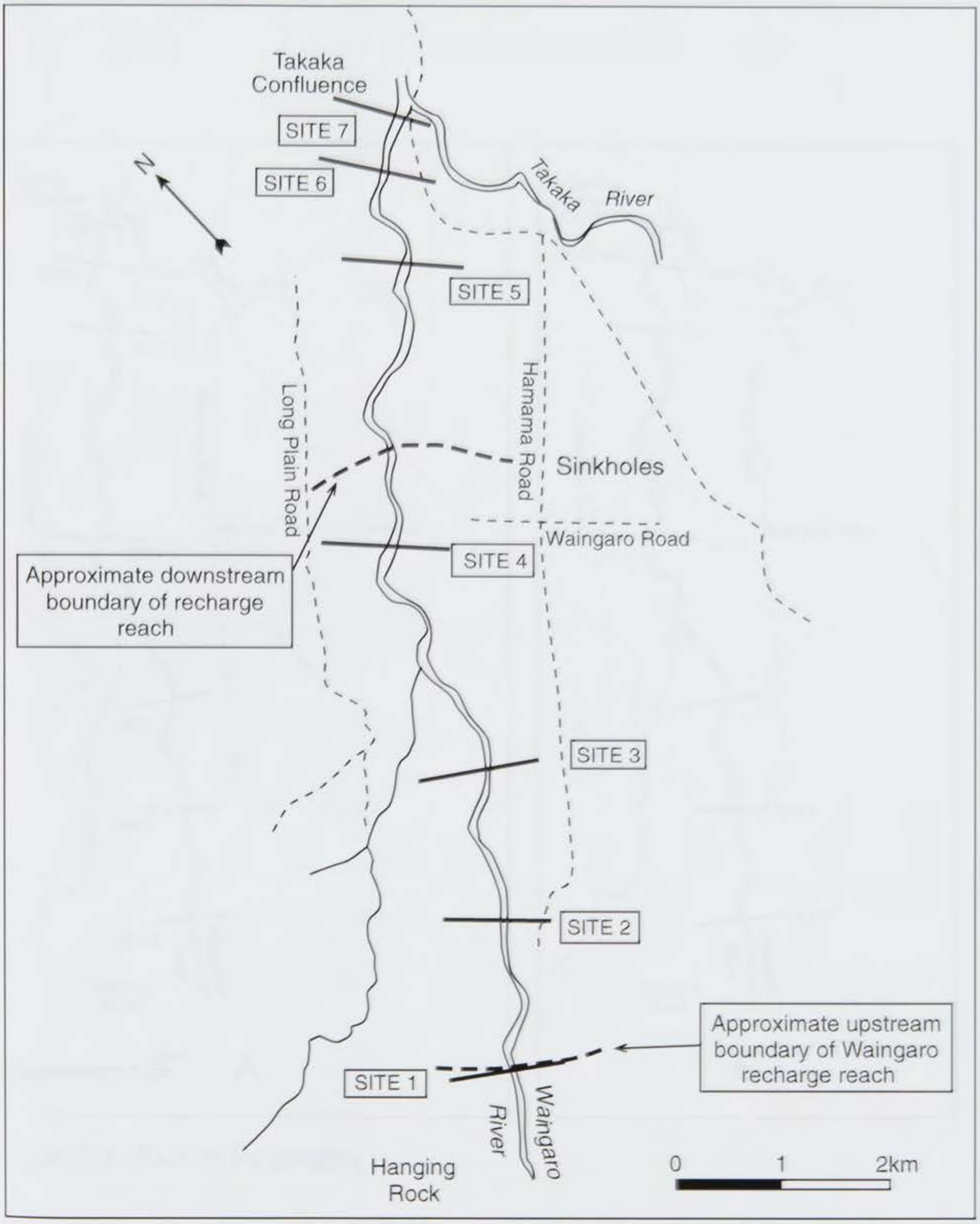


Figure 3.8: Location of Waingaro River gauging sites.

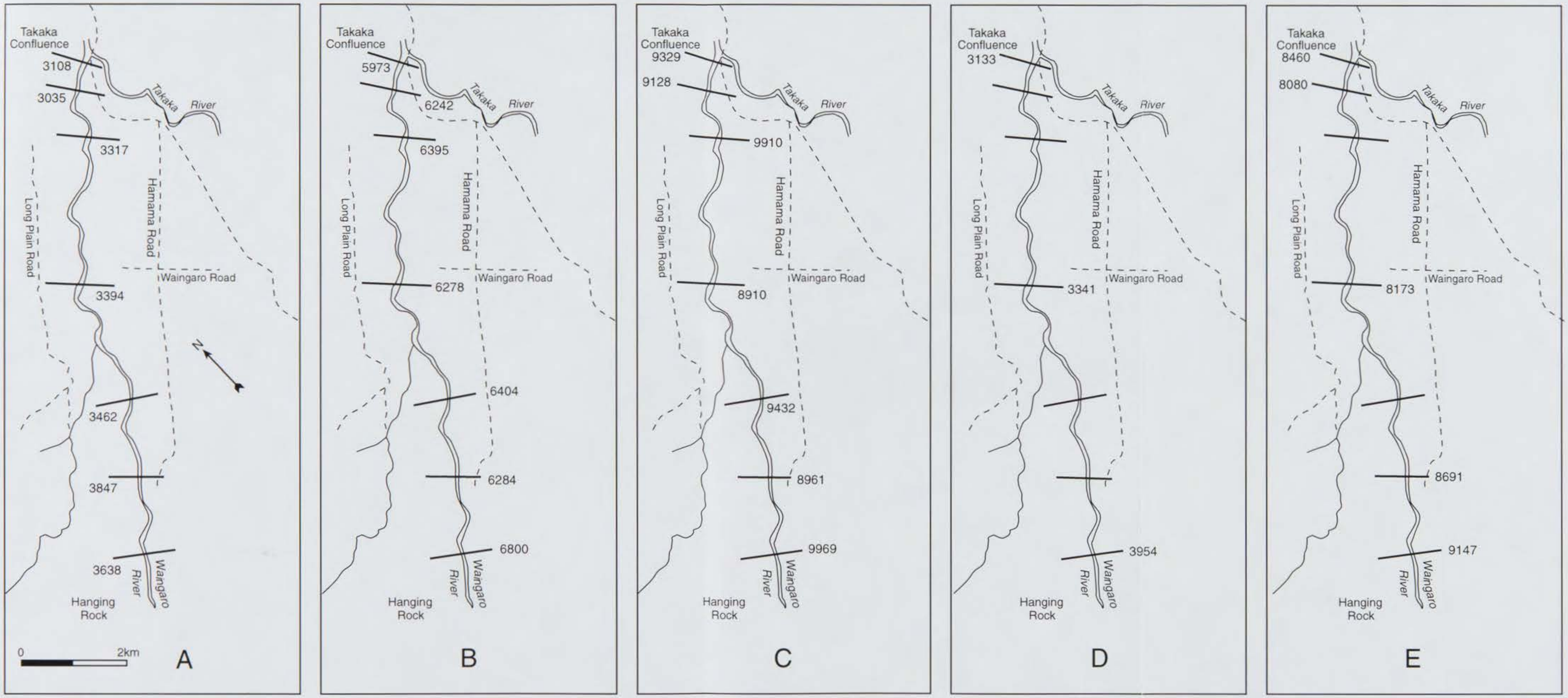


Figure 3.9: Results for gauging runs A - E along the Waingaro River recharge reach. Flow is given in litres/sec.

Table 3.4. Details of selected Waingaro gauging runs. Units are l/s.

	Site 1 (M26 889296)	Site 2 (M26 896306)	Site 3 (N26 915335)	Site 4 (N26 929350)
A	3638	3847	3462	3394
B	6800	6284	6404	6278
C	9969	8961	9432	8910
D	3954	nm	nm	3341
E	9147	8691	nm	8173

nm = not measured

B) Evidence for Waingaro river sink contribution

An estimate of the mean contribution of the Waingaro river sinks to the WAM Aquifer is of the order of 0.5-1.5 m^3s^{-1} (based on the mean derived from selected gauging runs A-E, and on hydrograph analysis). Confirmation of this can be derived from the analysis of a series of input and output hydrographs. Under certain meteorological conditions, rainfall events can be confined to or isolated in the Waingaro subcatchment. An example of such an event is shown in Figure 3.10, along with the resultant spring discharge,. The rise in Waikoropupu Springs discharge from 16660-17510 l/s (Figure 3.10) is the result of a flood event in the upper Waingaro catchment of the order of 125000 l/s. The commencement of rise in the Waikoropupu Springs discharge precedes minor increases in the Upper Takaka River.

Overall the contribution via the Waingaro river sinks is minimal compared with that derived from the Takaka River. The Waingaro River contribution has been added to the total input from tributaries. The imbalance will be derived from additional stream sink contribution and diffuse recharge.

3.2.3.3 Flow loss in the Anatoki River

The Anatoki River crosses a band of Arthur Marble (disrupted by Wangapeka Formation) which stretches approximately 1.5 km between the small open Happy Sams Valley to upstream of the Golden Bay Fault (faulted contact between the Arthur Marble and Onekaka Schist). Recharge contribution to the WAM Aquifer via the Anatoki river sinks

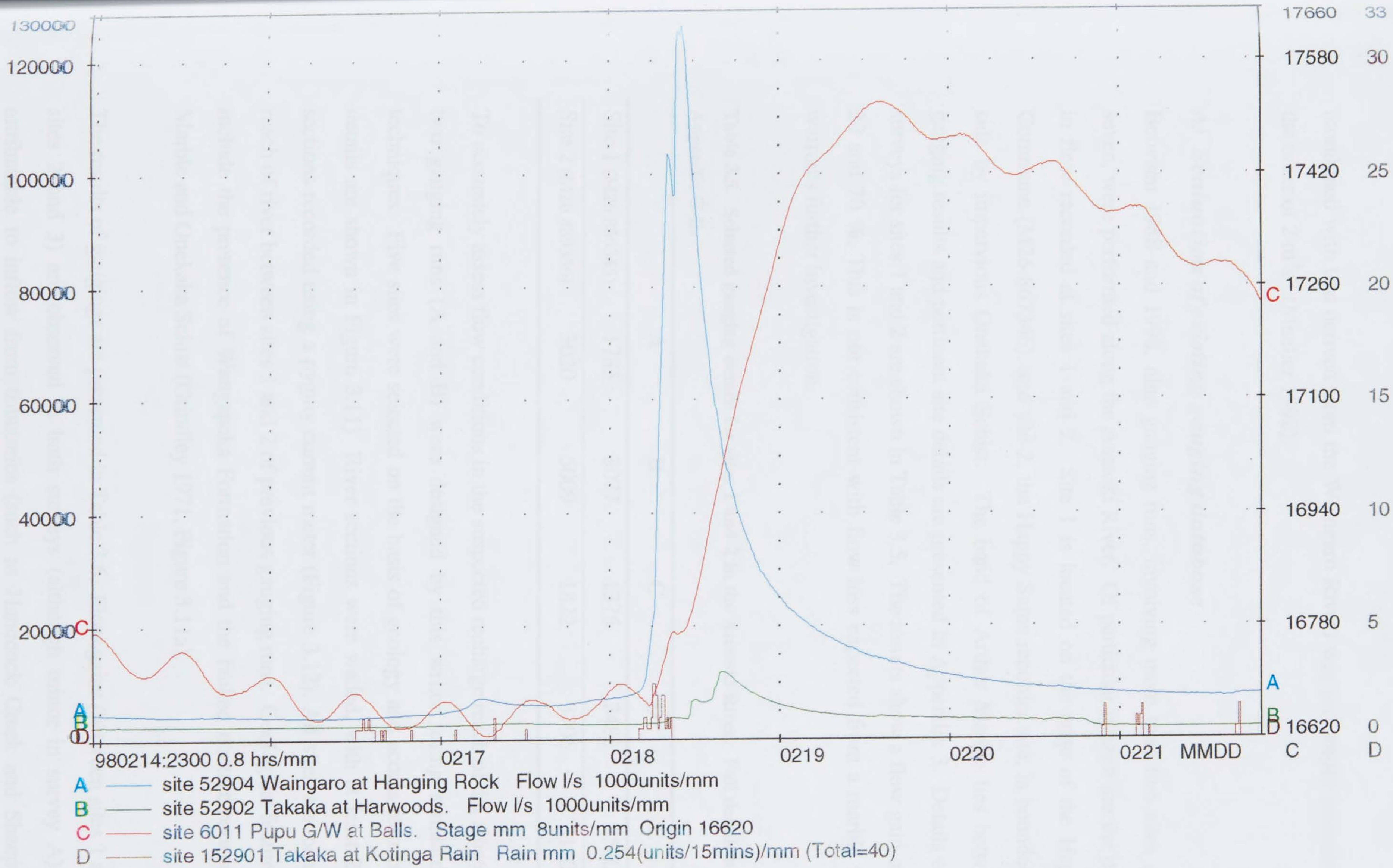


Figure 3.10. Hydrograph overplot of Waingaro River flow (at Hanging Rock), Balls groundwater level, Takaka River flow (at Harwoods), and Kotinga rainfall station (Data period extends from 14 February to 21 February 1998)

(combined with that derived from the Waingaro River) was previously assumed to be of the order of 2 m^3s^{-1} (Mueller 1992).

A) Evaluation of existing gauging database

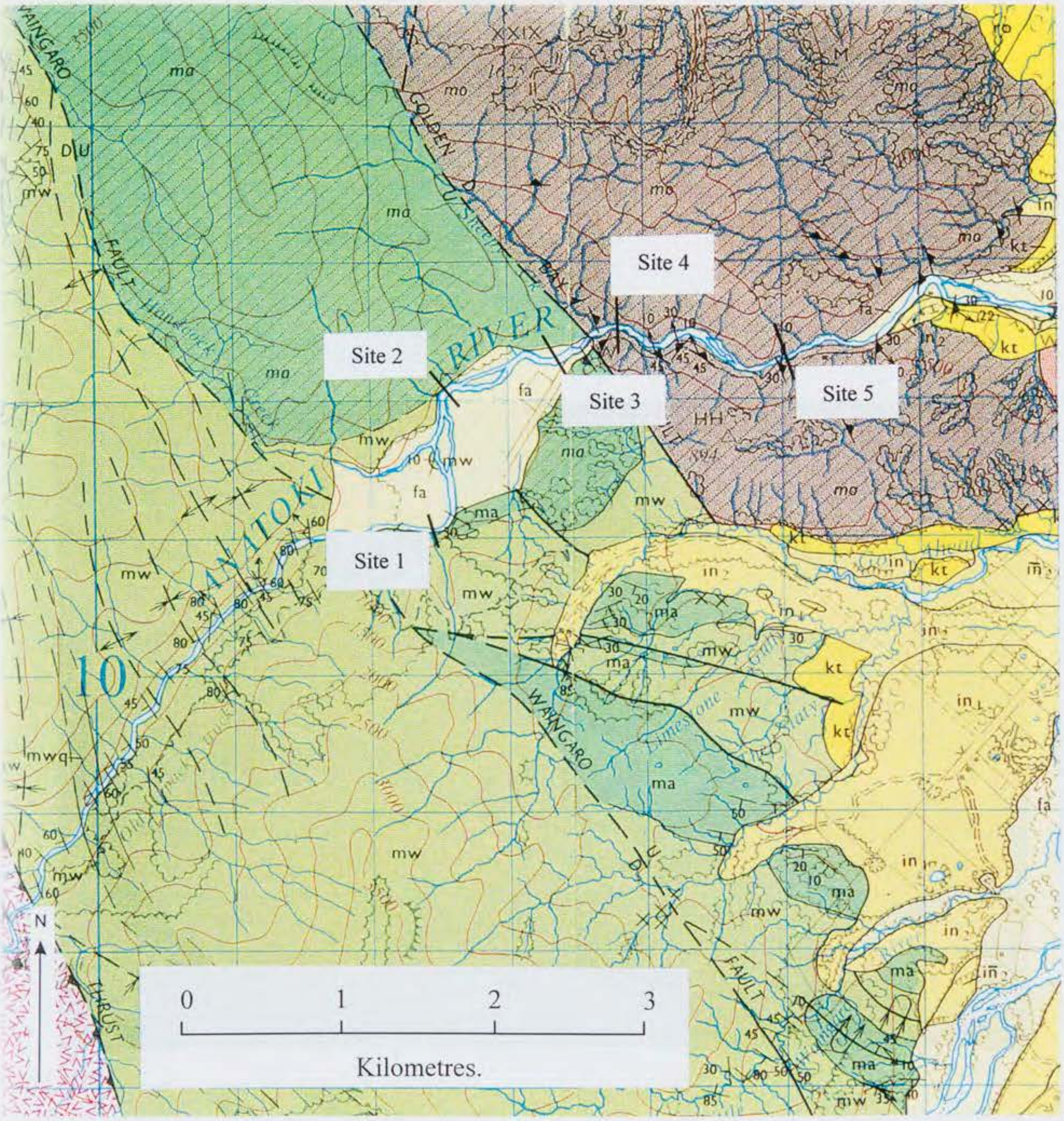
Between 1988 and 1998, nine gauging runs, involving more than two sites and up to seven, were performed along the Anatoki River. Of particular interest are the differences in flow recorded at sites 1 and 2. Site 1 is located on the edge of the Happy Sams Commune (M26 867346), and site 2, the Happy Sams recorder site, is bounded on each side by impervious Onekaka Schist. The band of Arthur Marble lies between. All gauging results and pertinent site details are presented in Appendix 3. Details of selected surveys for sites 1 and 2 are shown in Table 3.5. The results show a flow gain of between 20 and 70 %. This is not consistent with flow loss expected from a marble zone, and warrants further investigation.

Table 3.5. Selected gauging details for sites 1 and 2 in the Anatoki River. Full details are given in Appendix C-II.

	A	B	C	D	E
Site 1 (M26 866345)	1785	3077	1376	2483	2540
Site 2 (M26 889356)	3020	5009	1822	3706	3120

To accurately assess flow conditions in the suspected recharge reach of the Anatoki River, two gauging runs (A and B) were designed by this writer, using standard gauging techniques. Five sites were selected on the basis of geology and access restrictions (site details are shown in Figure 3.11) River sections were waded, with at least 20 vertical sections recorded using a pygmy current meter (Figure 3.12). All sites are located in the reach of river between sites 1 and 2 of previous gauging runs. Geological features of note include the presence of Wangapeka Formation and the faulted contact between Arthur Marble and Onekaka Schist (Grindley 1971, Figure 3.11a).

The results of gaugings are presented in Table 3.6. Flow gains (between sites 1 and 2, and sites 2 and 3) are observed in both surveys (although minor in survey A), and are attributable to inflow from tributaries (such as Handcock Creek and Sheepy Creek). Results of flow fluctuations between sites 3 and 4 are inconsistent. A substantial gain of



SITE 1	M26 866345	Quaternary deposits
SITE 2	M26 866352	
SITE 3	M26 873356	Wangapeka Formation
SITE 4	M26 878357	Onekaka Schist
SITE 5	M26 889356	Arthur Marble

Figure 3.11. Location of Anatoki River gauging sites (1-5), grid references from NZMS 260, Sheet M26

Figure 3.12. Gauging the Anatoki River (site 4)

15 % (350 l/s) is observed in survey A, while a loss of 5 % (217 l/s) is observed in survey B. Sites 3 and 4 are located upstream and downstream of the Golden Bay Fault respectively. Flow is stable between sites 4 and 5 in survey A, with minimal increases in survey B.

Table 3.6. Flow data (l/s) for sites shown in Figure 3.11.

	Survey A	Survey B
Site 1	2117	3546
Site 2	2153	4203
Site 3	2252	4616
Site 4	2608	4399
Site 5	2600	4542

Within the suspected recharge reach, the gauging data in the main branch of the Anatoki River is inconsistent. No definitive loss zone can be identified (unlike the Takaka and Waingaro Rivers). It is likely that Wangapeka Formation provides an impervious basement between sites 1 and 2 The most likely position geologically for a loss zone is between sites 2 and 3. Flow gains, however, are observed in this section; the presence of an impermeable layer within the gravel is a possible explanation, and further gaugings over a range of input flows would be needed to clarify this. The role of the faulted boundary as a discharge/recharge zone cannot be determined. Recorded flow values upstream (site 4) and downstream (site 5) of the faulted boundary are inconsistent.

For the purposes of this thesis, contribution to the WAM aquifer system via a river sink arrangement in the Anatoki River is assumed to be negligible. Losses downstream of site 5 (or site 2 in the original gauging investigations) contribute to the surrounding gravels, and not to Arthur Marble.

3.2.3.4 Recharge contribution from tributary stream sinks

Seventeen named streams and creeks in the Central Valley subcatchment contribute to the WAM aquifer system. The total contributing catchment area of these is approximately 100 km^2 (Figure 3.1). Sixteen of the tributaries cross (in some part) Arthur Marble; one tributary, Scott Creek, has Arthur Marble in its entire catchment. Approximately 55 km^2

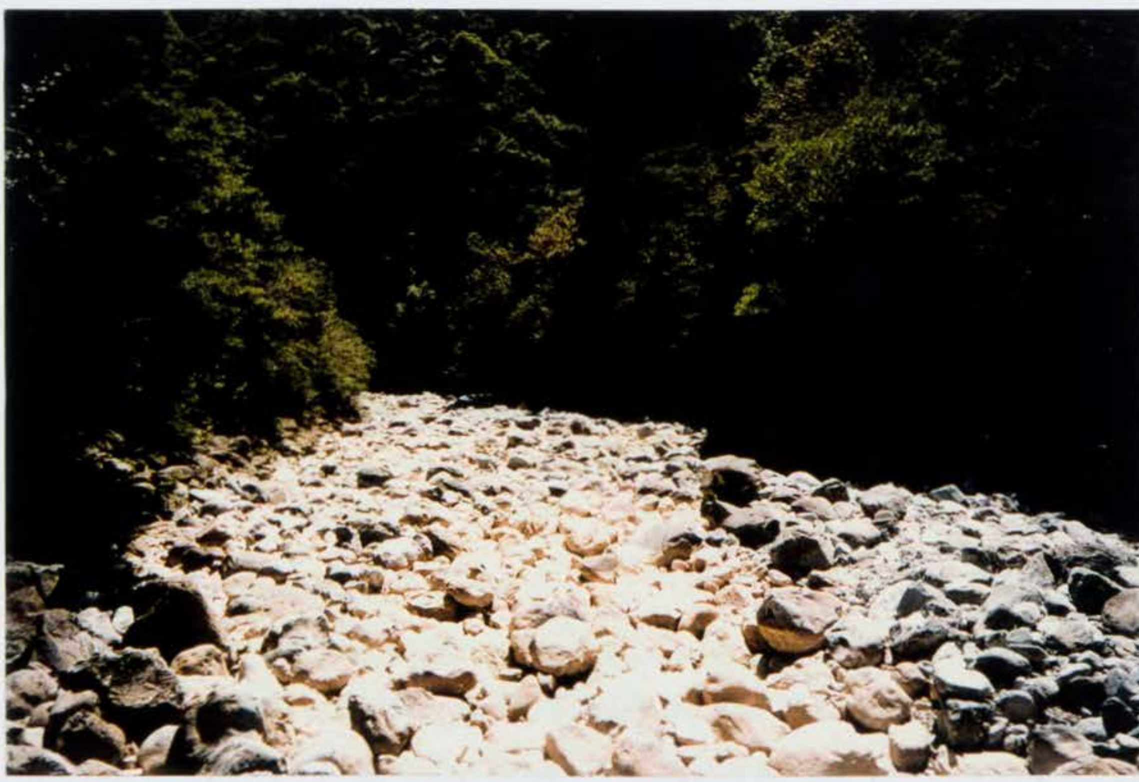
of the total contributing area has Arthur marble cropping out; the rest is composed of Pikikiruna Schist, Separation Point Granite deposits, Riwaka Diorite, and Quaternary and recent deposits. Previous estimates of recharge contribution from tributary stream sinks by Mueller (1992) were of the order of 8.2 m^3s^{-1}.

The majority of the tributary streams and creeks in the Eastern and Western ranges retain flow only in their upper reaches. Gauging sites are selected in the uppermost sections of Arthur Marble outcrops above water take schemes, so that maximum flow is recorded. Flow is only observed down an entire reach shortly after periods of intense rainfall (this occurs on average 15-20 times per year). Flow is typically sustained along an entire reach for periods of days only. Typical summer low flow figures measured in Gorge Creek (Figure 3.13) and Craigieburn Creek and collected on 20 March 1998 are 314 l/s and 199 l/s respectively.. Estimates of other stream flows investigated during visits in the summers of 1997 and 1998 (from Sams Creek, Cotton Creek, Stoney Creek, Ironstone Creek, Scott Creek, and Rameka Creek) are of the order of 50-200 l/s.

A permanent recorder exists for Rameka Creek, situated at Pages Ford (N26 997327). The site is run to gather flow characteristics of this particular eastern tributary, in order to assess its potential for a proposed private hydro-scheme. Useful flow characteristics are as follows: mean discharge (June 1993-June 1997) is approximately 200 l/s, standard deviation is 323 (to 3sf), maximum flow is 11053 l/s (25 August 1993), and minimum is 68 l/s (1 October 1996). Only after heavy rainfall does flow continue down the mainstem to the Rameka Creek-Takaka River confluence (at N26 939371).

Based on a contributing area of 100 km^2, total precipitation of 2600 mm yr^{-1}, and assumed surface runoff of 30-50 %, the contribution to groundwater via tributary stream sinks would be of the order of 4-5.5 m^3s^{-1}, equivalent to approximately 140 $m^3yr^{-1} \times 10^5$. This is substantially lower than the figure derived by Mueller (1992). Tributary sink contribution is an important component of concentrated allogenic recharge input, and together with the Waingaro River contributes some 30 % of inputs of the WAM Aquifer.

a



b

Figure 3.13. (a) Stream flow in Gorge Creek (upper reaches)
(b) Dry stream conditions, observed for approximately 800 m upstream from the Gorge Creek-Takaka River confluence (photos taken March 16 1998)

3.2.4 Diffuse autogenic recharge and allogenic recharge

Diffuse recharge (both autogenic and allogenic) is assumed to provide most of the remaining input to the WAM system (some 20%). Diffuse autogenic recharge enters the WAM aquifer system via Arthur Marble outcrops which cover an approximate area of 65 km^2. Primary recharge locations include the Eastern foothills and the plateau of the Pikikiruna Range. Recharge sites cover an altitudinal range of 100 m - 1000 m. Other areas include a band of Arthur Marble stretching from Sams Creek (West Takaka-N26 940230) to Hamama (Central Valley N26 920319). Diffuse allogenic recharge occurs within the unconfined section of the WAM aquifer over an approximate area of 25 km^2. Precipitation input does not have a direct connection to the Arthur Marble, and total contribution is dependent of infiltration percentage, which is high for the Takaka River channel and immediate surrounds.

Diffuse input is estimated to contribute 15-20 % of WAM input. Estimation of actual inputs have been calculated in the WAM Aquifer water balance presented in section 6.3.

3.2.5 Other sources of recharge input

3.2.5.1 Semi-concentrated autogenic recharge through dolines

Depressions provide a means by which autogenic inputs can be concentrated, and have been recognised as an important source of point recharge in some karstic settings (Gunn 1983). In the Takaka Valley the volume input is small compared to recharge derived from other allogenic sources, because of the relatively small surface areas of individual dolines. The total surface area designated to autogenic recharge dolines is trivial; estimation has not been attempted, and input has been incorporated in diffuse autogenic recharge.

3.2.5.2 Inter-aquifer recharge

While it is likely that inter-aquifer recharge occurs between the confined section of the WAM Aquifer and the ETML Aquifer, through the East Takaka Fault system (Grapes 1994), it is impossible to quantify. Evidence to support the existence of potential inter-aquifer leakage/recharge pathways is gained from geophysical sections, which display fault disruption in Motupipi Coal Measures, Takaka Limestone and Tarakohe Mudstone (Ravens 1991). Disruption through all major formations provides a probable recharge/leakage pathway.

3.3 DISCHARGE SITES

3.3.1 Methodology adopted

The identification and measurement of discharge sites are critical components of an aquifer's water balance. Karst springs, which usually occur at the lowest elevation in a karst system (i.e. at a site of minimum head), drain water from the dynamic storage of an aquifer (White 1988). The form of a spring discharge hydrograph can yield useful information about the nature and operation of a karst drainage system (Ford and Williams 1989). The following topics are discussed:

- the geological, geomorphological, and hydrological siting of springs,
- the measurement and characteristics of discharge, and
- hydrograph analysis.

Elaborate analysis of hydraulic setting, such as the work done by Bakalowicz and Mangin (1980) on the effects of turbulent flow in a karst spring system, has not been possible for the WAM Aquifer, as there is a definite lack of hydraulic information and control. Discussion of conduit structure has likewise been omitted. Discharge discussions are understood to be read in association with evaluation of spring water quality (Chapter Five), and WAM Aquifer water balance (Chapter Six).

3.3.2 Discharge styles and classification

Various classification schemes have been proposed for karst springs (Ford and Williams 1989, Bogli 1980) according to geological and tectonic conditions (bedding, fracture, overflow springs), outflow (perennial, periodic, episodic, rhythmic springs), or inflow origin (emergence, resurgence, exsurgence springs). Certain elements of discharge classification are incorporated into the sections that follow.

3.3.3 The Waikoropupu Springs system

3.3.3.1 Siting and description of springs

Waikoropupu Springs are the primary discharge point of the WAM aquifer. They are located approximately 4 km south of the Golden Bay coastline in the Waikoropupu Valley, and vary in elevation from 14 to 17 metres above sea level. The total springs system covers an area of 4.5 km^2 and incorporates approximately 16 vents. These are subdivided into three sub-systems termed Main Springs, Dancing Sands, and Fish Creek Springs (Figure 3.14).

The siting of the Waikoropupu Springs is geologically controlled, aligned in a NNW orientation parallel to the faulted boundary between Cretaceous Onahau Granite and Ordovician Arthur Marble (Figure 2.1, Grindley 1971). Artesian conditions prevail. Water derived from the WAM Aquifer emerges from an estimated 10-20 m covering of Tertiary Motupipi Coal Measures at the Main Springs site (Broadbent 1987), and from a shallow veneer of gravels (approx. 5-10 m) at Fish Creek Springs.

Orifices of Main Springs are approximately 4.6 m below the water surface, with basal depths of 6.9 m (Rapier 1975). The emerging water at Main Springs is under hydrostatic pressure and displays the characteristic "domed turbulent boil" (Ford and Williams 1989) typical of artesian springs. Dancing Sands comprises one major vent and several minor ones: these emerge approximately 2.7 m below the water surface (Rapier 1975), where sand particles are observed to move and bounce. The bathymetry of these two sub-systems was surveyed by Michaelis (1976). Both Main Springs and Dancing Sands drain to the Springs River, which joins the Waikoropupu River 500 m downstream.

Fish Creek Springs, made up of at least 5 small vents, is located 240 m south-west of Main Springs and 3 m higher in elevation. Vents are dispersed and are on a smaller scale than those of Main Springs. Fish Creek Springs has been known to run dry. All vents drain to Fish Creek, which joins the Springs River 150 m from Main Springs (Figure 3.14).

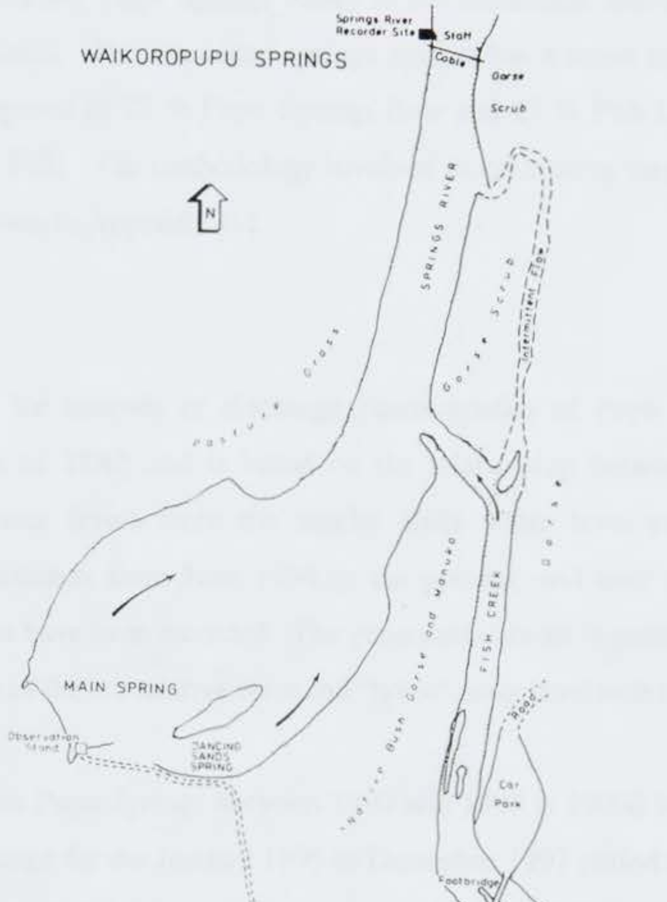


Figure 3.14. Waikoropupu Springs and the Springs River
(Adapted from Williams 1992, Williams 1997, Rapier 1975)

3.3.3.2 Discharge measurement and characteristics

A) Combined springs system

In the sections which follow, Pupu Springs refers to the combined discharge of Main Springs and Dancing Sands. The combined springs system has a mean annual flow of 13253 l/s. This is composed of 77 % Pupu Springs flow and 23 % Fish Creek Springs contribution (Appendix F-II). The methodology involved in calculating total spring flow and its components is given in Appendix F-I.

B) Pupu Springs

The main record used for analysis of discharge characteristics of Pupu Springs was generated by M. Doyle of TDC, and is based on the relationship between individual gaugings and groundwater levels from the nearby Balls water level recorder (N26 902394). The record extends from June 1994 to the present, and over this period a number of rating changes have been recorded. The generated data set is preferred over the original data set because of the cumulative error and "noise" associated with the latter.

The mean discharge from Pupu Springs between 1990 and 1997 is 10000 l/s. Summary statistics of spring discharge for the January 1995 to December 1997 period are presented in Table 3.7. Minimum and maximum discharges recorded are 7312 l/s (4 April 1997) and 12459 l/s (30 September 1995) respectively. Minimal seasonal variation in spring discharge is observed during the calendar year, with mean monthly flow variation of the order of 200-500 l/s. Differences are apparent, however, in mean flows between dry and wet (or wetter) years. The 1997 monthly means from January to May are consistently lower than those observed in 1995 or 1996 (Table 3.7), and are reflective of the extended dry spells experienced in that year. Total rainfall from the Kotinga station (N26 939373) for the January to May period in 1995, 1996, and 1997 is 1079 mm, 902 mm, and 442 mm respectively.

C) Fish Creek Springs

The Fish Creek gauging station (N26 905397) measures components of spring flow and overland flow derived from Fish Creek and Fish Gully. An alternative record,

SUMMARY STATISTICS FOR MAIN PUPU SPRINGS (1994-1997)												
	January	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**
1995												
Minimum	8036	9908	10153	9978	10235	10217	10258	10193	10254	10510	10231	9352
Maximum	10771	11621	11348	11941	11623	11161	10908	11173	12549	12437	11123	12198
Mean	9384	10631	10515	10718	10744	10495	10516	10509	10906	11377	10609	10585
1996												
Minimum	9975	9493	9255	8938	9501	9334	9241	9703	9880	9860	9712	na
Maximum	11775	10317	10911	11048	10331	10134	11507	11131	11367	11699	10982	na
Mean	10664	9871	9964	10032	9775	9614	10186	10177	10500	10484	10256	na
1997												
Minimum	9345	8377	7462	7312	8710	9367	9822	9564	10282	na	na	na
Maximum	10139	10047	8831	9481	10072	11488	10429	11016	11328	na	na	na
Mean	9768	9362	8173	8841	9151	10029	10067	10341	10719	10760	9870	10090

na = data not available

Table 3.7. Monthly mean, minimum, and maximum discharge for Pupu Springs (data period 1994-1997)

representing spring discharge only, has been generated using the relationship between Fish Creek Springs discharge and Balls groundwater levels (M Doyle TDC). This record used the rating created by the Balls water level versus Fish Creek flow, taking the lower envelope of flow to represent surface base flow. Gaugings showed the surface baseflow to be 1%: this was then subtracted before the rating was drawn The rating is unlikely to change unless the connection between Fish Creek Springs and Balls water level recorder changes (pers. comm. Doyle 1998).

Fish Creek Springs mean annual discharge is estimated to be 3300 l/s for the period April 1990 to Sept 1997. Summary statistics for the January 1995 to December 1997 period are presented in Table 3.8. Minimum and maximum flows recorded are 53 l/s (April 1997) and 6961 l/s (September 1995). The mean monthly discharge is variable; the highest discharge is generally associated with the winter and spring months of July, August, and September. Fish Creek Springs discharge can change dramatically between months (for example between January and February 1995), and is highly variable between dry and wet (or wetter) years. Mean discharge over the first six months of 1997 was well below mean levels. In April 1997, Fish Creek Springs virtually ceased, and flow is reduced to 73 l/s (7 April). For 32 days in the months of March and April, recorded flow is under 1000 l/s (i.e. well below mean levels).

3.3.3.3 Hydrograph analysis

A) Analysis methods

The shape of the outflow hydrograph recorded at a spring is a unique reflection of the response of the aquifer to recharge (Ford and Williams 1989). The most instructive hydrographs are those of abrupt, intense storms which inject sharp pulses of water into the karst system (White 1988). The spring response time to recharge events will be variable. For example, a system dominated by allogenic recharge, with a well developed conduit system, has a "flashy" response to storms, while the response of an aquifer system with mostly diffuse flow, poorly developed conduits, and little allogenic recharge is much more subdued (White 1988). Ford and Williams (1989) present a number of different hydrograph responses, which range from broad, flat, muted graphs to sharp, peaked responses.

SUMMARY STATISTICS FOR FISH CREEK SPRING FLOW (1994-1997)												
	January	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**
1995												
Minimum	451	3054	3402	3157	3516	3419	3550	3458	3544	3904	3512	2283
Maximum	4245	5527	5128	5999	5531	4854	4483	4871	6961	6780	4797	6400
Mean	2182	4089	3915	4213	4246	3886	3915	3906	4486	5174	4048	4033
1996												
Minimum	3340	2808	2929	2521	3260	3041	2919	3525	3757	3730	3447	na
Maximum	5840	3971	4935	5324	4347	4090	5965	5440	5769	6252	5042	na
Mean	4246	3380	3745	3958	3618	3407	4167	4149	4579	4563	4111	na
1997												
Minimum	2273	902	105	53	1349	2203	2293	1744	2836	na	na	na
Maximum	3383	3254	1520	2464	3288	5161	3325	3967	4451	na	na	na
Mean	2864	2289	708	1167	1984	3072	2732	2926	3504	3558	2211	2543

na = data not available

Table 3.7. Monthly mean, minimum, and maximum discharge for Fish Creek Springs (data period 1994-1997)

The form and rate of recession can provide significant information on the storage and structural characteristics of an aquifer system (Ford and Williams 1989). The fundamentals of recession analysis were first presented by Maillet (1905). He proposed that the discharge of a spring is a function of the volume of water held in storage, and is described by the simple exponential relation:

$$Q_t = Q_o\, e^{-\alpha}$$

where Q_t = discharge at time t

Q_o = initial discharge

t = time elapsed in days between Q_t and Q_o

e = 2.71 (to 3sf)

α = recession coefficient

In an ideal system, the receding limb of a hydrograph is an exponential curve which eventually brings the discharge back to base flow, providing later storms do not intercede (White 1988). When the receding limb is plotted on semi-logarithmic axes, the resulting plot will be a straight line with slope α, the recession coefficient. Under simple recession (Ford and Williams 1989) the plot will have one linear segment. More complex situations arise when part or all of the plot is non-linear (Ford and Williams 1989 present equations to deal with this), or when the plot is made up of more than one linear segment.

B) Pupu Springs

Pupu Springs hydrographs have typically steep rising limbs, rounded crests (as opposed to peaked), and slower receding limbs (providing no additional storms intercede). Hydrographs show a distinct rhythmic response to tidal influences, which are of the order of twice daily 5 mm increases and decreases in spring height. During storm response the quickly rising spring flow masks out the tidal effects. It is important to note that the increases in spring discharge are a result of pressure pulse transmissions and not of actual throughflow of water.

Figure 3.15 shows the hydrograph response for a distinct small input event, in March 1997. The background flow conditions are low, and river and rainfall conditions are given. The time from initial rise to spring discharge peak is approximately 40 hours. The recession time from peak discharge to pre-event low flow conditions is of the order of 13 days. Recession would have continued if further input events had not interceeded. The lag time (time interval between centre of recharge excess to peak of resulting hydrograph) is approximately 20 hours. The lag between the commencement of rise in the Takaka River (Harwoods recorder) and the commencement of Pupu Spring discharge rise is of the order of 5-6 hours.

The hydrograph response for an input event during higher flows is shown in Figure 3.16. Rise to spring peak is approximately 30 hours (discharge increasing from 9808-11130 l/s), lag time (based on peak upper Takaka River flow and mid valley rainfall) is of the order of 1 day, and the lag between commencement of recharge input and commencement of Pupu Spring discharge rise is of the order of 4 hours. Tidal influences are masked in both the rising limb and the initial segment of the falling limb. Recession is interrupted by interceding storm events.

A recession curve for January 1995 is plotted on semi-log axes in Figure 3.17. The plot is composed of multi-linear segments (which are difficult to identify). These segments imply a complex drainage system (Ford and Williams 1989), possibly made up of several components of flow.

C) Fish Creek Springs

Fish Creek Springs hydrographs typically display steep rising limbs, slightly rounded crests (although more peaked than the crests observed for Pupu Springs), and less steep receding limbs. Rhythmic oscillations are of the order of 13 mm, as compared with 5 mm for Pupu Springs. They are observed twice daily, and are correlated with tidal effects. Tidal fluctuations are masked when water level increases rapidly.

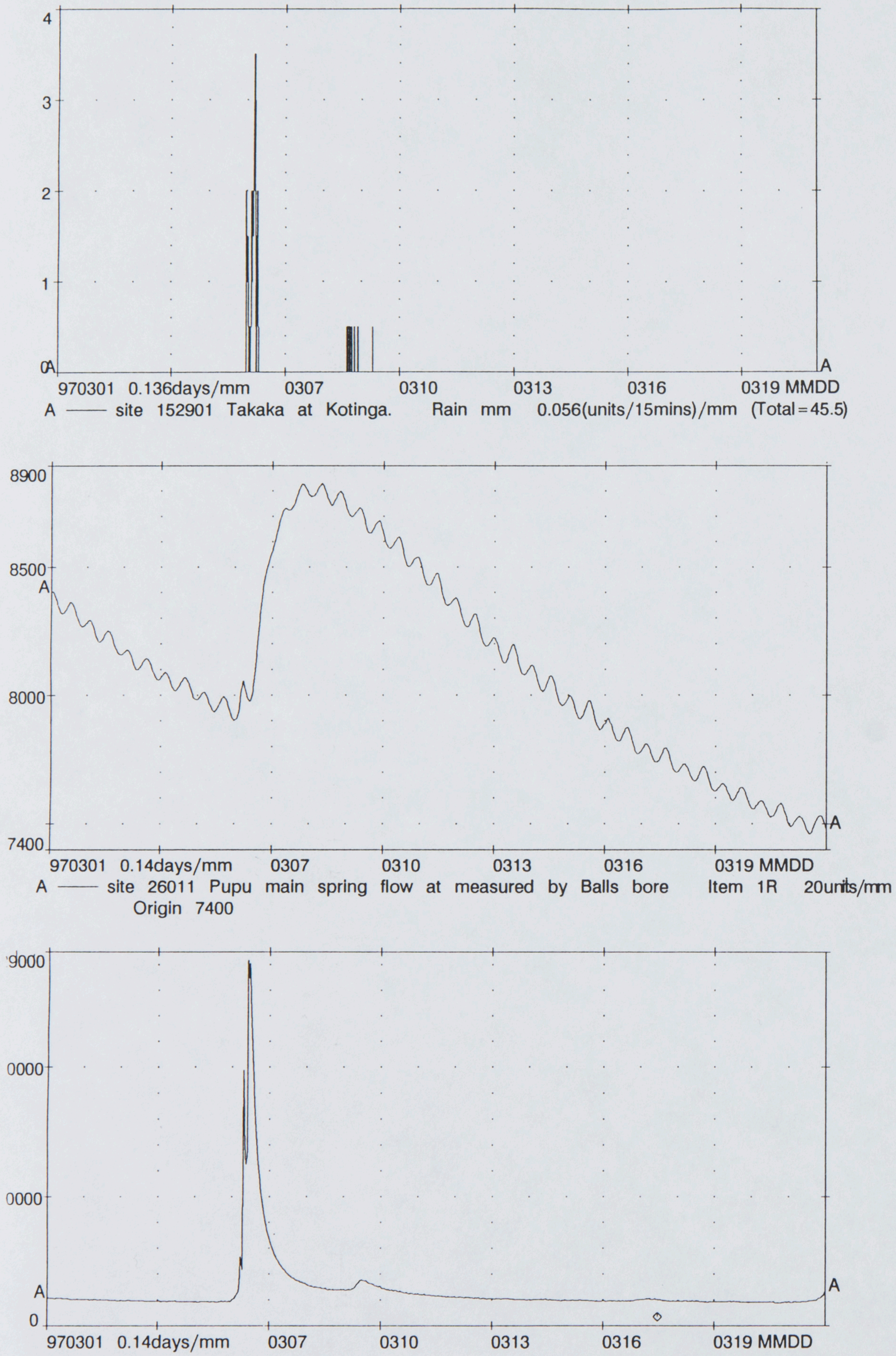


Figure 3.15. Hydrograph records of a recharge event under low flow conditions. Takaka River at Harwoods, rainfall at Kotinga, and Pupu Springs discharge are presented

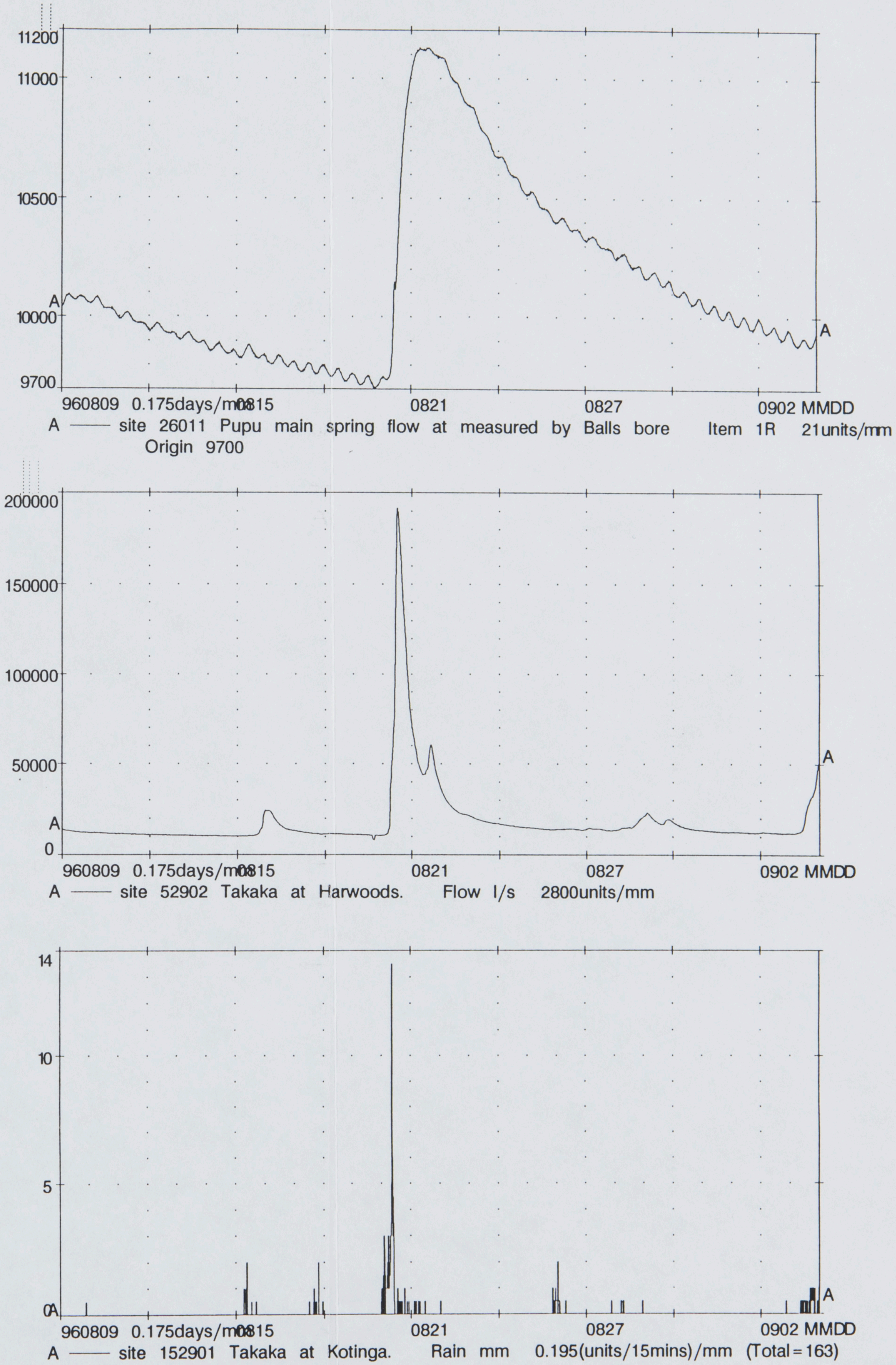
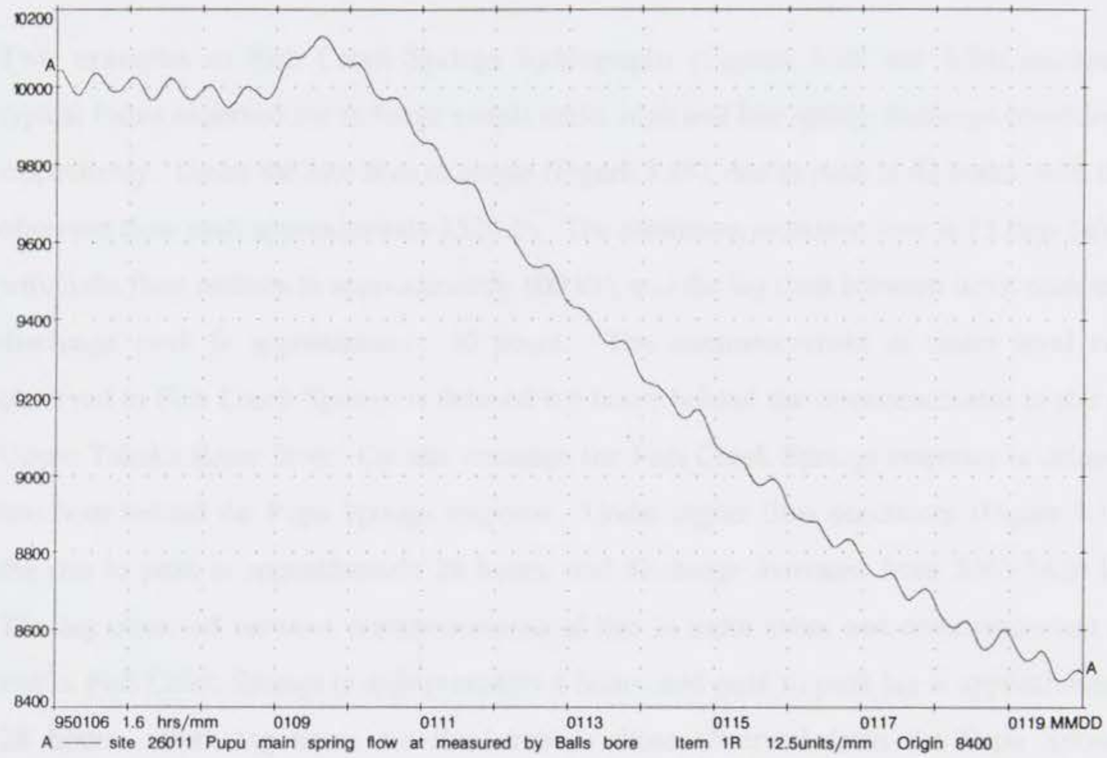


Figure 3.16. Hydrograph records of a recharge event under high flow conditions. Takaka River at Harwoods, rainfall at Kotinga, and Pupu Springs discharge are presented



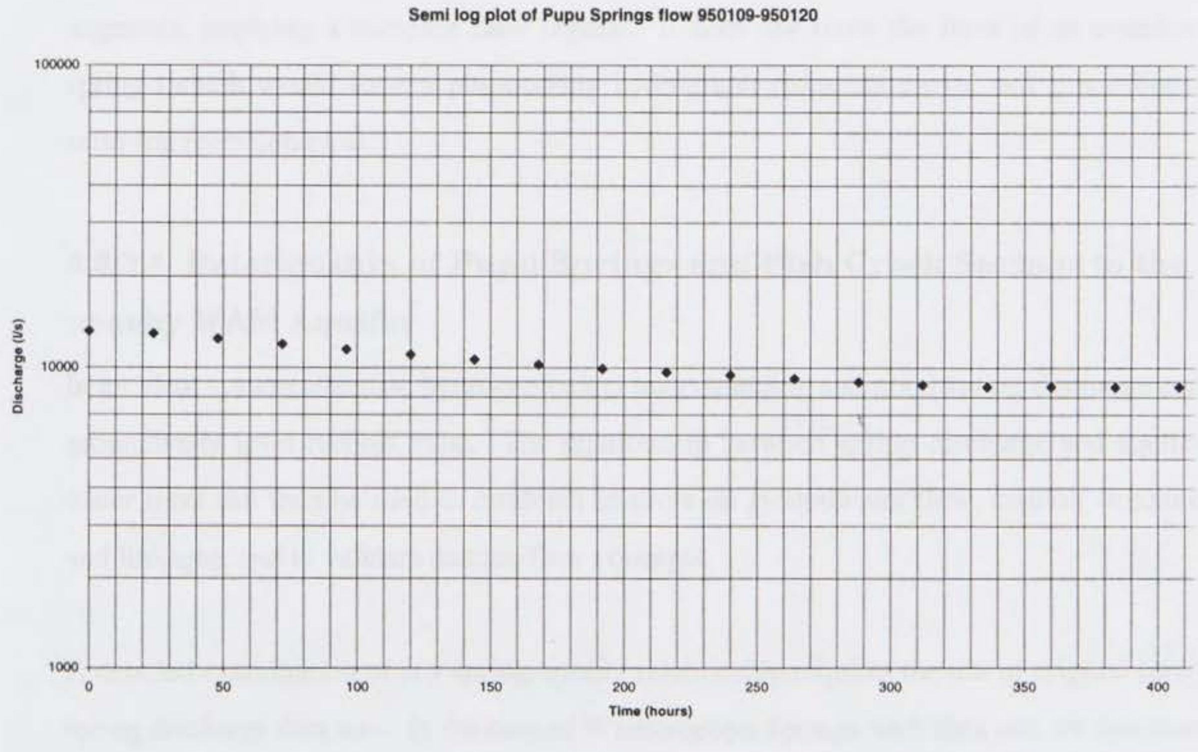


Figure 3.17. Recession characteristics of Pupu Springs. Selected data period is January 1995

Two examples of Fish Creek Springs hydrographs (Figures 3.18 and 3.19) represent typical forms observed for recharge events under high and low spring discharge conditions respectively. Under the low flow example (Figure 3.18), rise to peak is 42 hours, with the observed flow peak approximately 1520 l/s. The minimum recession time is 13 days (after which the flow reduces to approximately 100 l/s), and the lag time between input peak and discharge peak is approximately 40 hours. The commencement in water level rise observed in Fish Creek Springs is delayed 6.5 hours behind the commencement in rise of Upper Takaka River flow. On this occasion the Fish Creek Springs response is delayed one hour behind the Pupu Springs response. Under higher flow conditions (Figure 3.19) the rise to peak is approximately 28 hours, and discharge increases from 3663-5420 l/s. The lag observed between commencement of rise in input event and commencement of rise in Fish Creek Springs is approximately 4 hours, and peak to peak lag is approximately 28 hours. Both lag times are the same as those observed from the Pupu Springs hydrographs (Figure 3.16).

Typical recession characteristics of Fish Creek Springs are shown in Figure 3.20. The semi-log recession plot during June and early July 1997 is composed of multi-linear segments, implying a complex flow regime. It does not show the form of an overflow spring (which would have a plummeting hydrograph recession curve, and a non-linear semi-log recession plot).

3.3.3.4 Relationship of Pupu Springs and Fish Creek Springs to the nearby WAM Aquifer

In an ideal system adequate hydrogeological understanding and good spring discharge and groundwater level records exist. The relationship between spring discharge and aquifer water level can then be used to establish controls on groundwater flow, conduit structure and linkages, and to validate darcian flow concepts.

A detailed examination of any spring-aquifer relationship requires the use of original (raw) spring discharge data sets. In the case of Waikoropupu Springs such data sets are less than ideal. Fish Creek records have a large surface component, while those for Pupu Springs are inherently "noisy". In order for the Balls record to be used to generate discharge data,

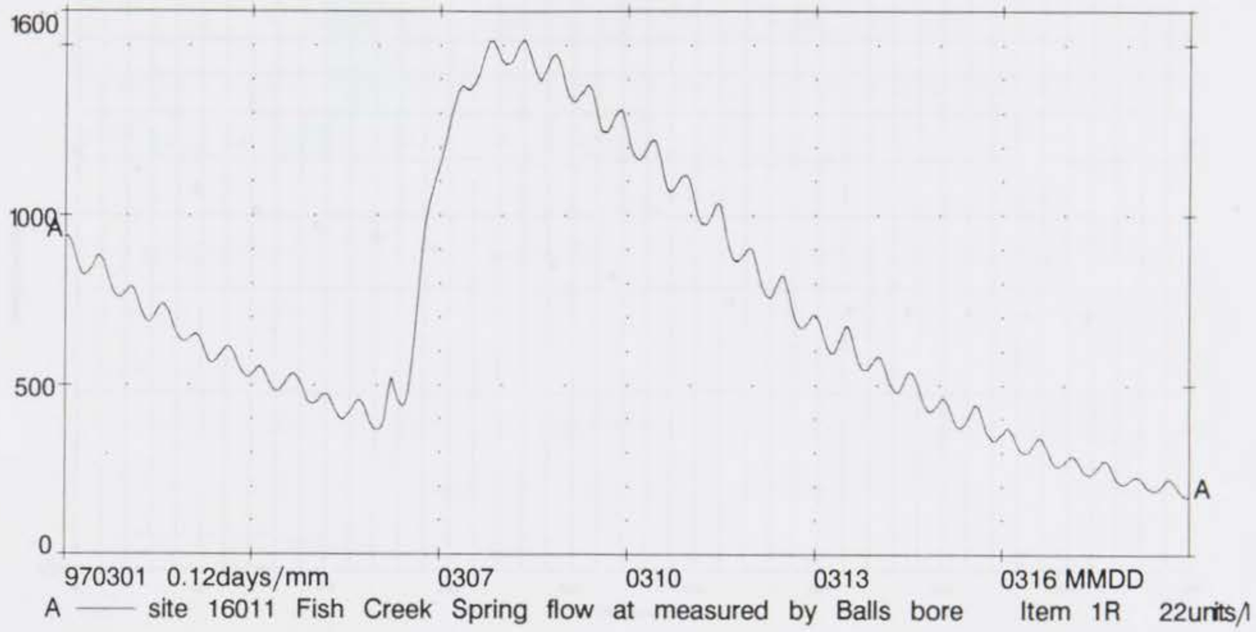


Figure 3.18. Fish Creek Springs hydrograph response to recharge under low background flow conditions. For rainfall and river hydrographs refer to Figure 3.15.

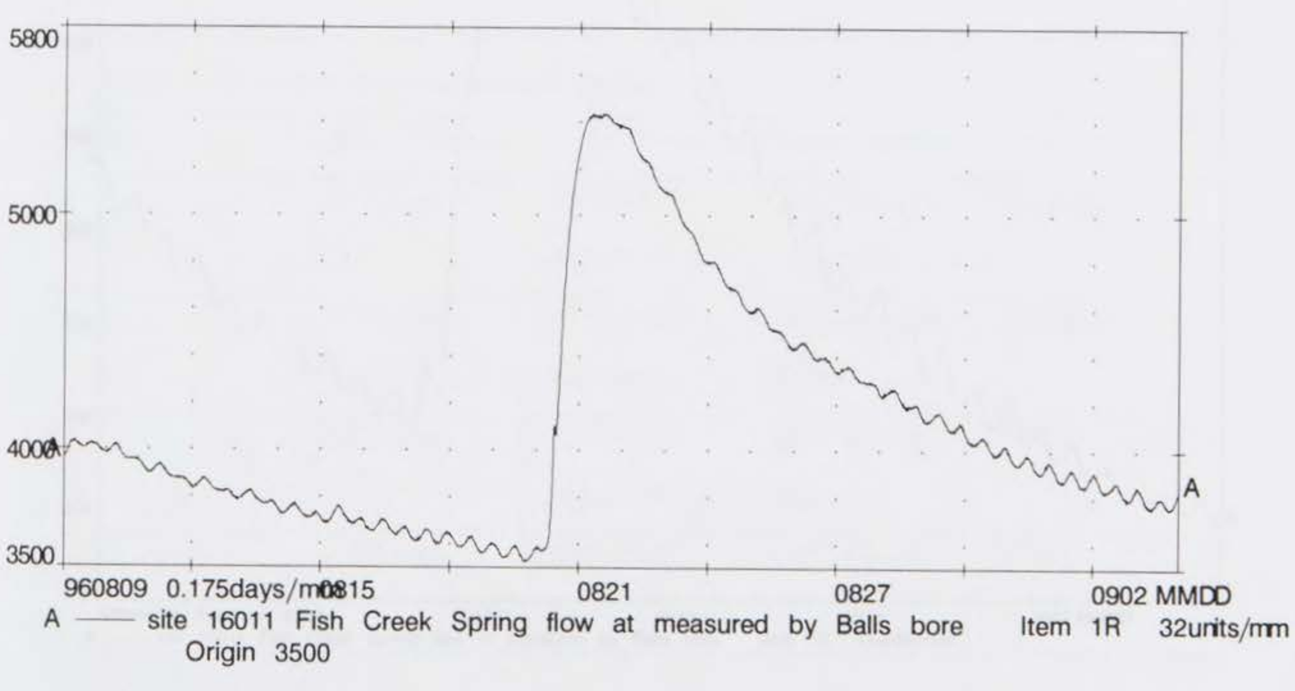
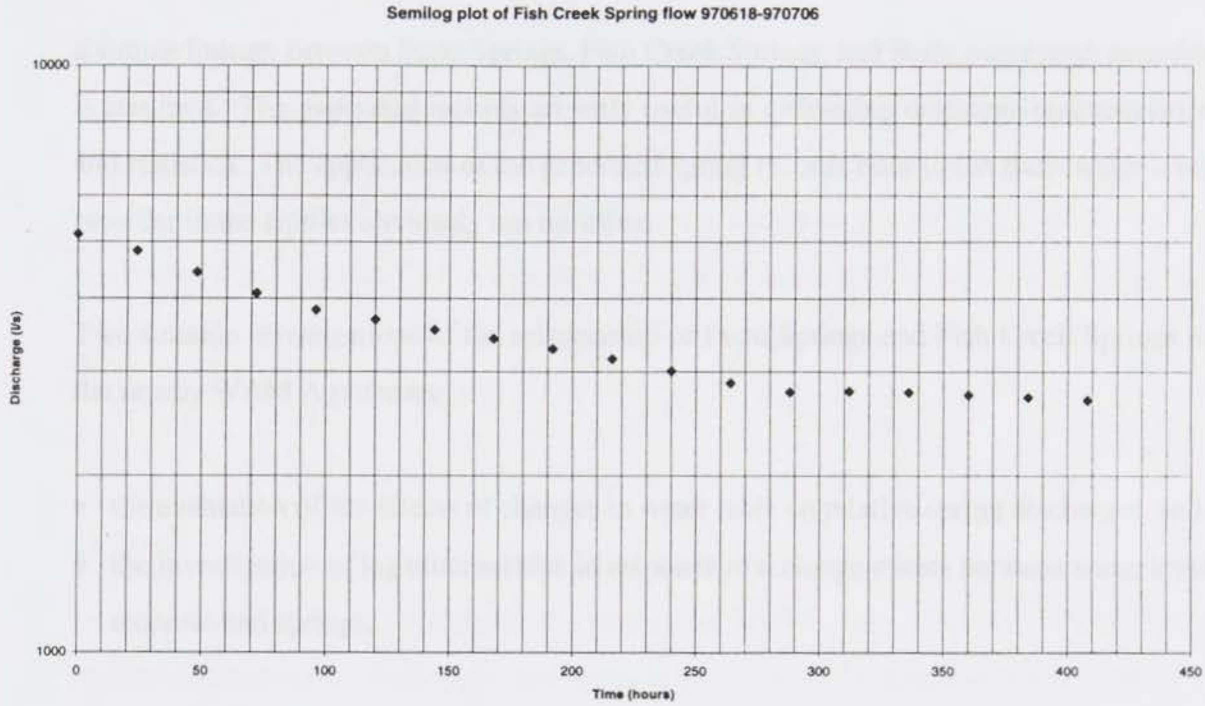


Figure 3.19. Fish Creek Springs hydrograph response to recharge under high background flow conditions For rainfall and river hydrographs refer to Figure 3.16.



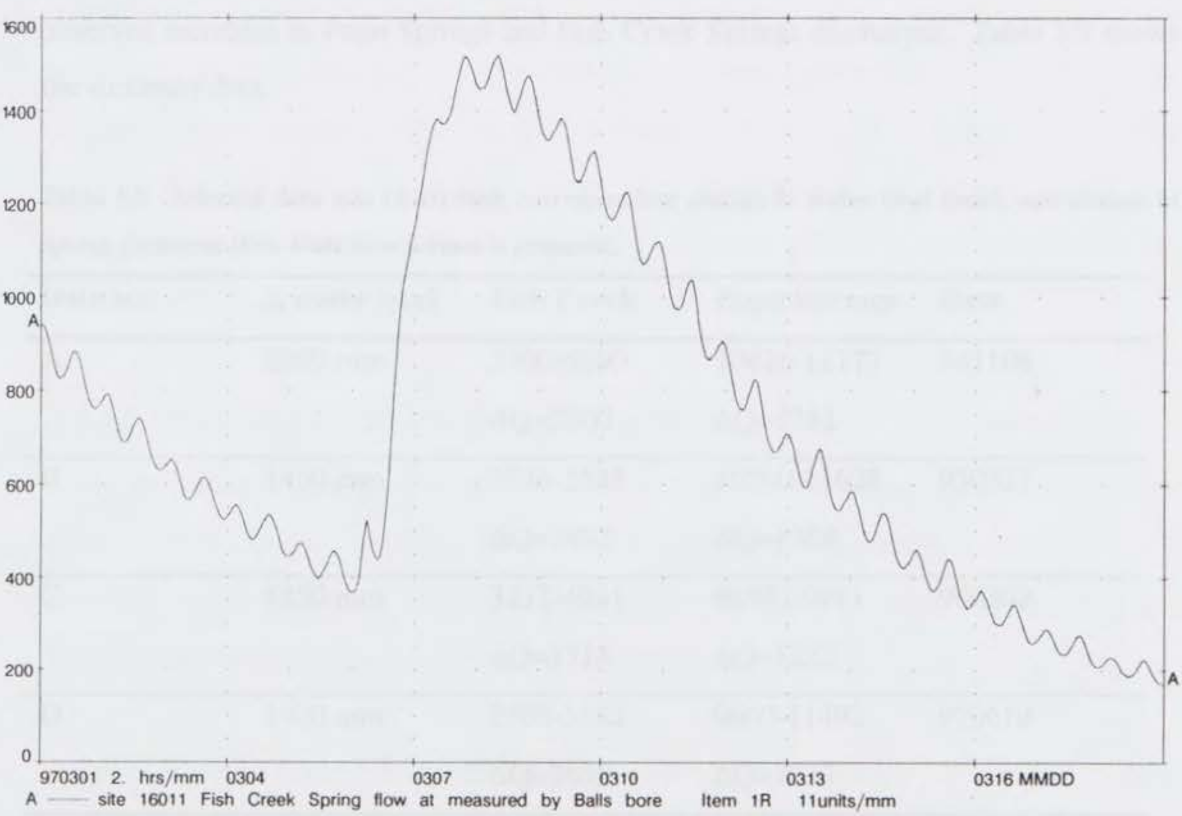


Figure 3.20. Recession characteristics of Fish Creek Springs. Selected data period is June-July 1997.

a simple linkage between Pupu Springs, Fish Creek Springs, and Balls water level recorder is assumed. The generated records are only useful in estimating discharge characteristics and statistics. The application of the generated spring records back to the Balls water level recorder in the aquifer obviously has no value.

Two suitable investigations of the relationship of Pupu Springs and Fish Creek Springs to the nearby WAM Aquifer are:

- the evaluation of the effects of changes in water table on relative spring discharges, and
- the investigation of lag relationships in response to recharge events between water level recorder and springs.

A) Water table fluctuations and spring discharge

To evaluate the effects of changes in water table on relative spring discharge, four selected data periods are analysed. Total change in water level is calculated, along with any observed increases in Pupu Springs and Fish Creek Springs discharges. Table 3.9 shows the summary data.

Table 3.9. Selected data sets (A-D) with corresponding change in water level (mm), and change in spring discharge (l/s). Date time format is yymmdd.

Data set	Δ water level	Fish Creek	Pupu Springs	Date
A	2050 mm	3300-6100	10426-12177	941106
		ΔQ=2800	ΔQ=1751	
B	1450 mm	3546-5538	10260-11628	950527
		ΔQ=1992	ΔQ=1368	
C	1250 mm	3217-4931	9659-10911	960302
		ΔQ=1714	ΔQ=1252	
D	1900 mm	2503-5162	9660-11492	970619
		ΔQ=2659	ΔQ=1832	

All input events result in changes in water table of greater than 1 m. Data sets A and D record water head changes of the order of 2 m and 1.9 m respectively (Table 3.9). Corresponding discharge increases for Pupu Springs (expressed as percentages of the original) are 17 % and 19 %; Fish Creek Springs increases are 83 % and 94 %, i.e. its discharge almost doubles. Data sets B and C record changes in water level of 1.5 m and 1.25 m respectively. Fish Creek Springs discharge increases approximately 50 %, whilst Pupu Springs increases a marginal 10 %.

B) Response pattern : lag

Balls water levels are plotted against gaugings recorded for Pupu Springs, in order to examine the pattern of any hysteresis curve that may occur. This will show if any appreciable lag exists in the response to recharge between Balls groundwater levels and Pupu Springs discharge.

22 gaugings were available, taken between June 1994 and October 1997. These are subdivided according to whether they were collected on rising limbs, during stable periods, or on recessing limbs (represented by different symbols in Figure 3.21). The resulting pattern shown in Figure 3.21 is non-linear, which suggests that there may be a small component of lag in response to recharge between the Balls recorder and Pupu Springs: a linear plot would indicate no time lag. No clear pattern of hysteresis is obvious, and further interpretation is precluded by insufficient data and high error.

3.3.3.5 Structure and functioning of Waikoropupu Springs system

A vertical hierarchy system can be envisaged to exist between Pupu Springs, Fish Creek Springs and the Balls water level recorder. Morphological evidence in support of this is gleaned from the heights of Pupu Springs and Fish Creek Springs relative to sea level, and from the fact that Fish Creek Springs is known to run dry.

Previous hydrogeological interpretation by Rapier (1975), Williams (1977), and Mueller (1992) considered Fish Creek Springs to be directly connected to (and operate as) an *overflow* mechanism of the Main Springs and Dancing Sands system. It is unlikely,

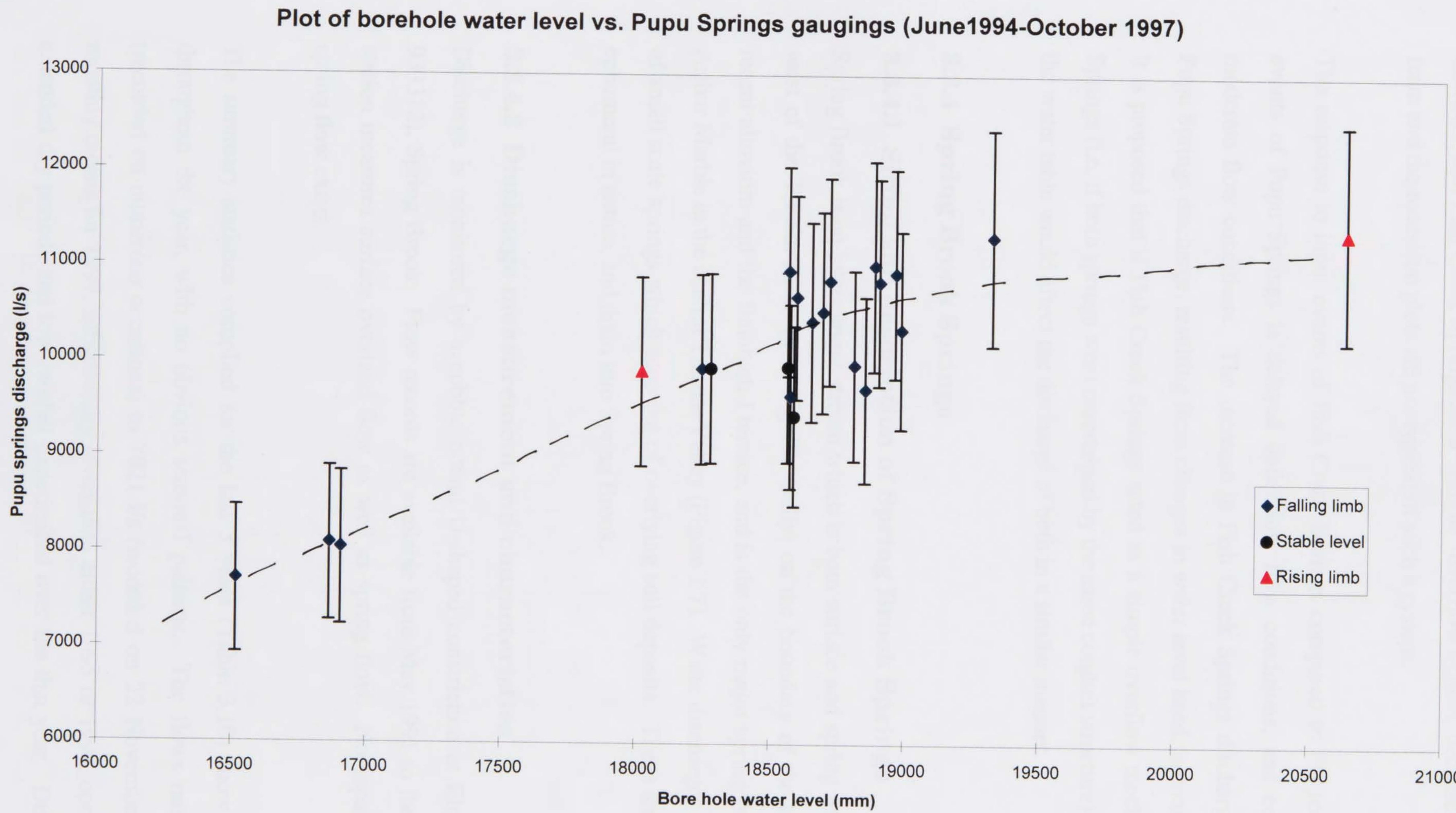


Figure 3.21. Plot of Balls borehole water level against Pupu Springs gauging. The dashed line is non-linear.

however, that Fish Creek Springs are a "simple" overflow system, because the hydrograph form and the recession plots are not typical of such a system.

The response to input events of Fish Creek Springs compared to the response to input events of Pupu Springs is delayed under low flow conditions, and equivalent under moderate flow conditions. The increase in Fish Creek Springs discharge compared to Pupu Springs discharge, resulting from changes in water level head, is consistently higher. It is proposed that if Fish Creek Springs acted as a simple overflow mechanism to Pupu Springs (i.e. if both springs were maintained by the same conduit structure), fluctuations in the water table would affect the discharge of both in a similar manner.

3.3.4 Spring Brook Springs

3.3.4.1 Siting and description of Spring Brook Springs

Spring Brook is an intermittent stream which is both surface and spring fed. It is located west of the Takaka River (near Pigville Gully) on the boundary of the terrace between recent alluvium and the Bainham I terrace, and is the only major spring issuing from the Arthur Marble in the central Takaka Valley (Figure 1.7). Water discharges from a number of small scale springs which seep out of overlying soil deposits. These small springs are ephemeral in nature, and drain into Spring Brook.

3.3.4.2 Discharge measurement and characteristics

Discharge is monitored by a cobble bound U-shaped constriction at Elm Grove (N26 933312), Spring Brook. Flow records are available from May 1991 to the present. The station measures surface overland flow as well as spring flow. No separate record for spring flow exists.

The summary statistics complied for the last 3 years (Table 3.10) show variable flow throughout the year, with no obvious seasonal patterns. The flows range from 0 l/s (recorded on numerous occasions) to 7021 l/s (recorded on 22 November 1995). The monthly means for 1997, substantially lower than either 1995 or 1996, correspond to the extended dry periods and low rainfall experienced over the that year. During 1997, nil

SUMMARY STATISTICS FOR SPRINGBROOK AT ELM GROVE (1994-1997)												
	January	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**
1995												
Minimum	0	109	1047	761	1145	1090	1195	1037	1150	1373	1040	0
Maximum	2479	7021	4551	4129	6854	2247	3306	4474	6407	3851	2352	7671
Mean	218	1675	1563	1827	1825	1508	1526	1487	1939	2071	1480	1382
1996												
Minimum	723	140	77	4	744	178	151	980	1200	1185	902	625
Maximum	4664	1251	3382	3668	2126	2683	2852	6537	3179	5895	2580	1624
Mean	1677	874	1268	1330	1166	797	1374	1578	1908	1722	1512	937
1997												
Minimum	0	0	0	0	0	0	0	0	282	na	na	na
Maximum	884	552	0	39	248	2746	317	1335	2222	na	na	na
Mean	419	118	0	4	28	560	81	501	na	na	na	na

na = not available

Table 3.7. Monthly mean, minimum, and maximum discharge for Spring Brook Springs (data period 1994-1997)

flow (corresponding to dry streams and no spring discharge) is recorded for a total of 95 days between January and August.

Precipitation data for the Harwoods recorder (the nearest station to Spring Brook) has been compared with Spring Brook flow data in Figure 3.23. As expected, rainfall variation has a direct effect on the discharge measured at Elm Grove.

3.3.4.3 Hydrograph analysis

Hydrographs of Spring Brook at Elm Grove are composed of two parts: peaks associated with overland flow (i.e. local rainfall input), and peaks associated with spring discharge. Of interest in this study are the hydrograph response and recession characteristics of the discharge component of Spring Brook. These will be used to build up a proposed model of spring flow. Spring Brook responses are variable, inconsistent, and complicated by the input of surface flow.

A selection of hydrographs and their associated recession curves (Figure 3.24(a)-(d)) have been chosen to highlight the inconsistent nature of Spring Brook response and are detailed as follows:

- Hydrograph (a), produced from a minor recharge event, shows a clear isolated rainfall spike. This is followed 2 days later by the Spring Brook response, i.e. a sharp rising limb, rounded peak, and more gradual recessing limb. A spring hydrograph of this form typifies a system in which gradual drainage is allowed through provision of independent storage. It displays a "well behaved recession" (pers. comm. Smart 1998).
- Hydrograph (b) does not have a clear rainfall spike preceding spring response. Both the rising and recessing limb are steep; a plummeting recessing limb of this type would be an expected response from an overflow spring. The accompanying semi-log recession plot is non linear, which is typical for overflow springs.
- Hydrographs (c) and (d) display variable spring response, namely both concave and convex receding limbs. The accompanying recession plots are nonlinear and inconsistent.

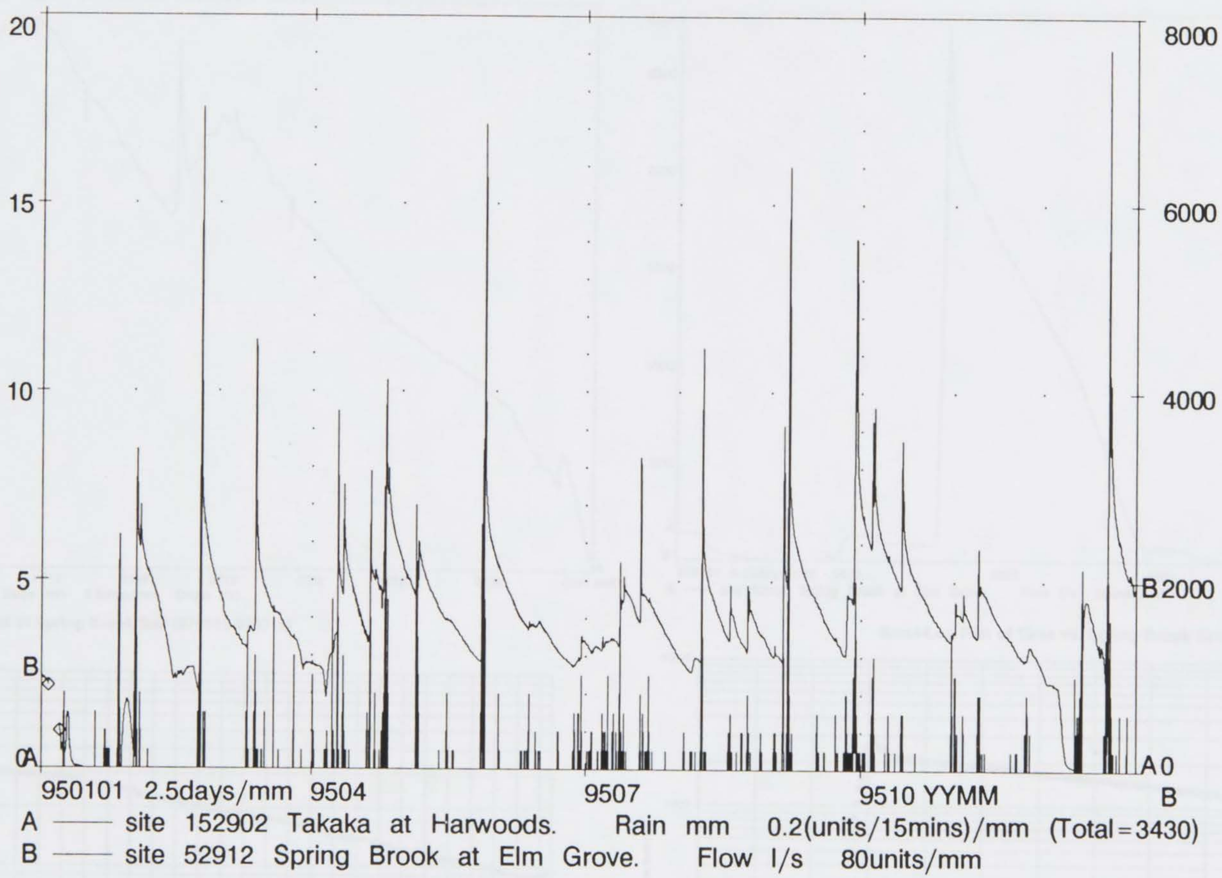
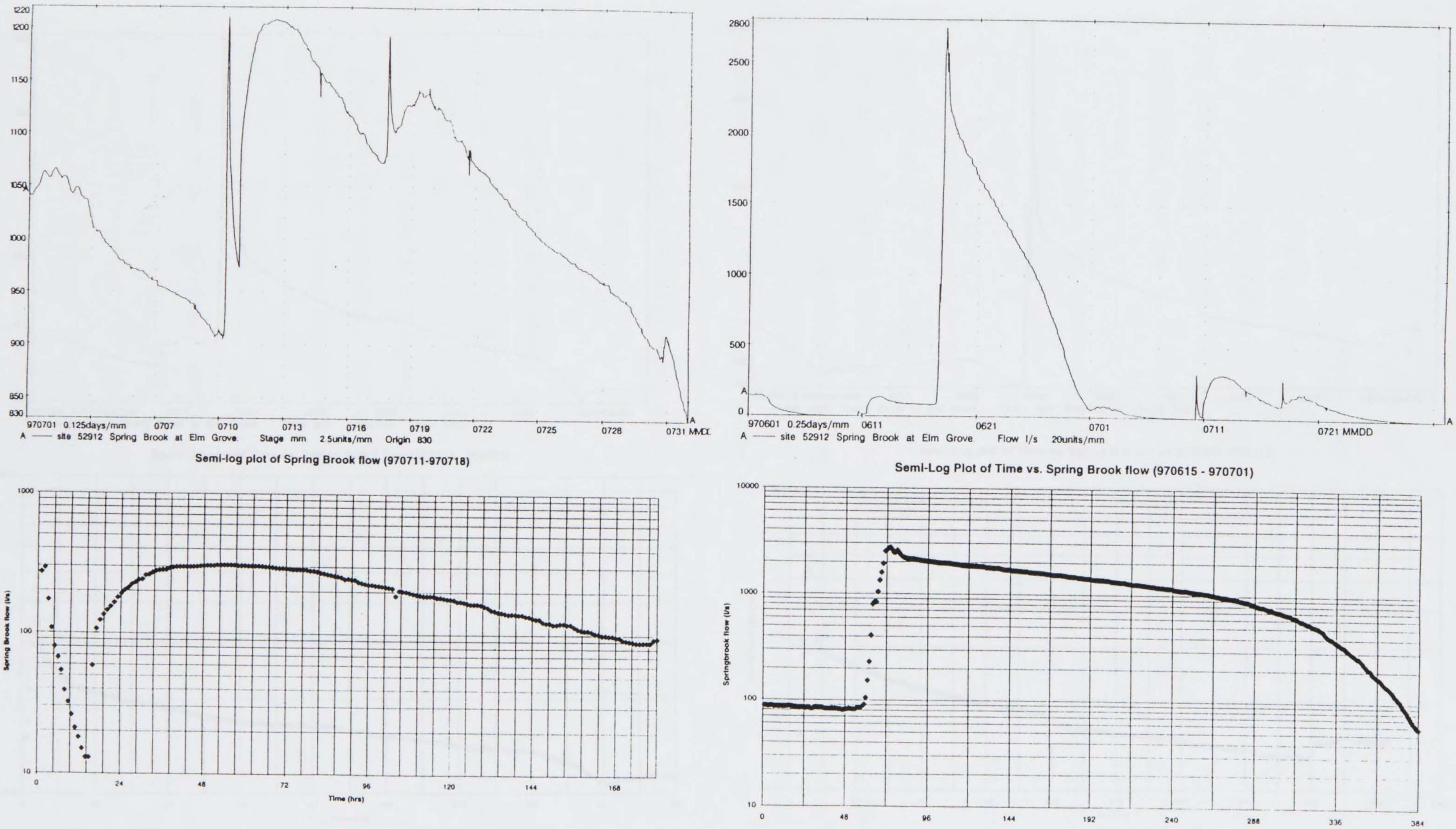


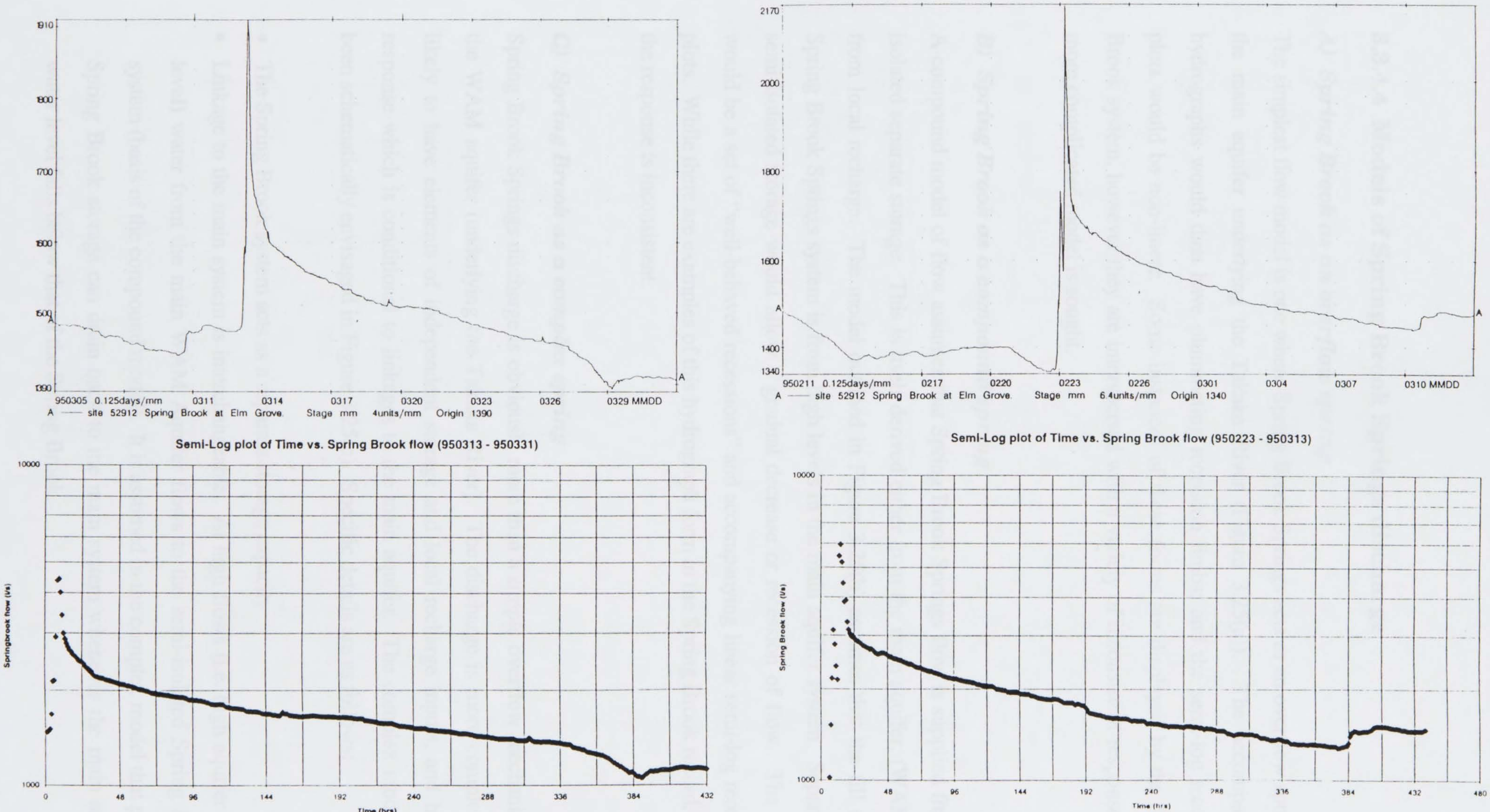
Figure 3.23. Overplot of Spring Brook Springs flow at Elm Grove (with additional input derived from overland flow) and Kotinga rainfall. Selected data period is 1995.



a

Figure 3.24a and b. Recession characteristics for Spring Brook Spring discharge

b



c   d.

Figure 3.24c and d. Recession characteristics for Spring Brook Spring discharge

3.3.4.4 Models of Spring Brook Springs discharge

A) Spring Brook as an overflow spring

The simplest flow model is one where Spring Brook Springs acts as an overflow spring to the main aquifer underlying the Takaka River (Figure 3.25(a)). The accompanying hydrographs would then have plummeting recession limbs; and the semi-log recession plots would be non-linear. Some instances of these forms are displayed by the Spring Brook system, however they are interspersed with a variety of inconsistent responses. A more complicated model is sought.

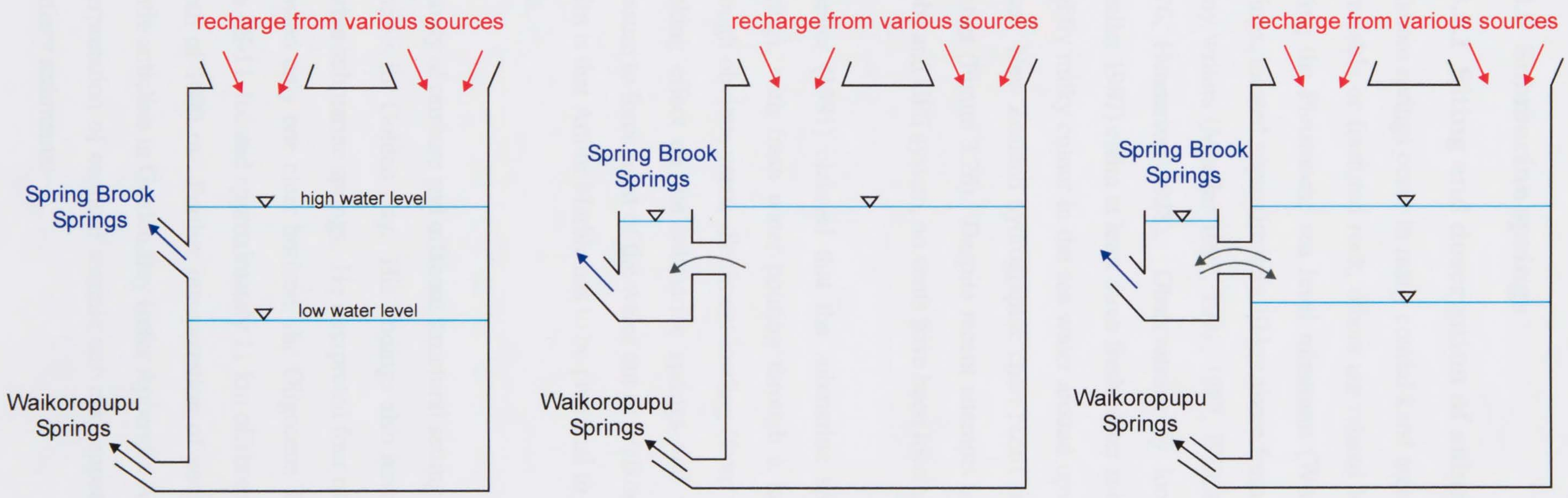
B) Spring Brook as a compound spring

A compound model of flow assumes that Spring Brook Springs flow is supplied from an isolated separate storage. This is itself derived either from the main aquifer, (WAM), or from local recharge. The model outlined in Figure 3.25(b) assumes that the fill of the Spring Brook Springs system is from high levels in the main aquifer system. Separate or semi-isolated storage would allow a gradual decrease or recession of flow. The result would be a set of "well-behaved recessions" and accompanying linear semi-log recession plots. While there are examples of this hydrograph form in the Spring Brook record, again the response is inconsistent.

C) Spring Brook as a complex spring

Spring Brook Springs discharge is obviously more than a simple overflow mechanism of the WAM aquifer (underlying the Takaka River). The discharge is more complex and likely to have elements of independent storage and local recharge inputs, and have a response which is conditional to linkages to the main aquifer. The complex model has been schematically envisaged in Figure 3.25(c). Specific details are as follows:

- The Spring Brook system acts as a separate storage capacity.
- Linkage to the main system is interchangeable. At high flows (i.e. high aquifer water level) water from the main WAM Aquifer flows to the semi-isolated Spring Brook system (basis of the compound model). It is assumed in the complex model that part of Spring Brook storage can drain back to the main system whenever the main aquifer water level falls below that of the Spring Brook.



a — simple flow model

b — compound flow model

c — complex flow model

Figure 3.25. Proposed flow models for Spring Brook Springs

3.3.5 Submarine springs

3.3.5.1 Siting and description of submarine springs

Offshore springs occur in many coastal karst areas. Some are fed by groundwater flow in permeable or fractured rock, others are related to karst feeder systems which developed during the Pleistocene sea level minimum (White 1988). The existence of submarine springs, located approximately 10 km shore from Rangiheata Head, has been proposed by many writers (Mueller 1992, 1991, 1987, Williams 1992, 1977, Rapier 1975, Michaelis 1976, Henderson 1928). Observations by local fisherpeople (cited in Rapier 1975, Mueller 1987) claim at least three fresh water submarine springs. Mueller (1991) noted a slightly milky colour in the sea water around upwellings, and lack of sea life in localised areas. New Zealand hydrographic chart NZ61 marks the possible location of three such springs (Figure 3.26). Despite recent attempts to locate the springs using a conductivity probe and GPS system, no vents have been located (pers. comm. Thomas 1998)..

Mueller (1991) claimed that the submarine springs would be similar to Fish Creek Springs, with fresh water pouring through a layer of gravel and boulders rather than through obvious vents. Sediment loading (from the nearby Takaka River) would cause a choking effect on the submarine springs and would create enough hydrostatic back-pressure to force most of the water out at Waikoropupu Springs. Inherent in this dubious claim is that Arthur Marble has to be proximal to the surface in the immediate Golden Bay area.

A study of onshore and offshore structural setting by Judd (1989) offered useful geological controls for Golden Bay. His findings also have direct implications for the existence of marble submarine springs. He interpreted four offshore seismic lines of poor quality; they showed only one clear horizon, the Oligocene Takaka Limestone. His interpretation of line FS-11, located approximately 11 km offshore, indicated the presence of limestone at a depth of 1000 m. Further interpretation of geophysical data showed a large symmetric gentle anticline in Golden Bay (refer Appendix A-III). Many of the faults (identified from interpretation of onshore seismic surveys) appeared to fade offshore, or to cease to cut Tertiary sediments.

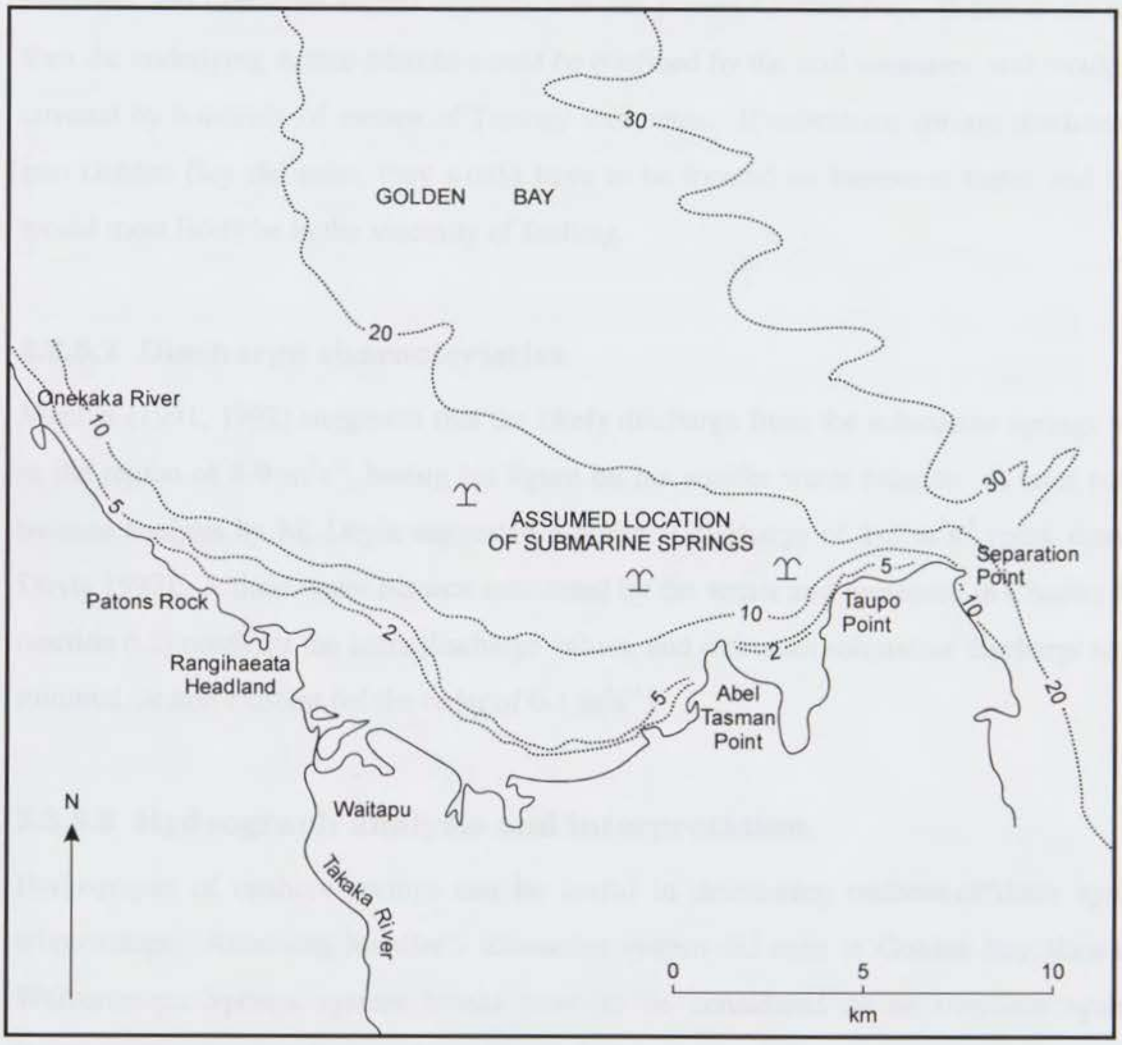


Figure 3.26. Bathymetric contours (in metres) and the assumed location of submarine springs in Golden Bay
Bathymetry data from Hydrographic Office of the Royal New Zealand Navy Map NZ 61 (1984)

There is no borehole information for Golden Bay; the nearest borehole is Fresne-1, located 20 km from the north end of Farewell Spit and drilled on a structural high. Additional information is available for the boreholes of the southern Taranaki Basin. Evaluation of these, along with isopach maps (King and Thrasher 1996), suggests that Tertiary coal measures and limestone extend offshore into the present Golden Bay. If this is the case then the underlying Arthur Marble would be confined by the coal measures, and would be covered by hundreds of metres of Tertiary sediments. If submarine springs discharging into Golden Bay did exist, they would have to be located on basement highs, and they would most likely be in the vicinity of faulting.

3.3.5.2 Discharge characteristics

Mueller (1991, 1992) suggested that the likely discharge from the submarine springs was in the region of 8-9 m^3s^{-1}, basing his figure on his aquifer water balance. A later water balance analysis by M. Doyle suggested a minimal discharge of 1-2 m^3s^{-1} (pers. comm. Doyle 1997). A third water balance calculated by the writer and presented in Chapter Six (section 6.2) confirms the latter discharge values, and estimates submarine discharge to be minimal, or non existent (of the order of 0-1 m^3s^{-1}).

3.3.5.3 Hydrograph analysis and interpretation

Hydrographs of onshore springs can be useful in delineating onshore-offshore spring relationships. Assuming Mueller's submarine system did exist in Golden Bay, then the Waikoropupu Springs system would have to be considered as an overflow spring. Response from an overflow spring with a submarine connection would be highly variable and the hydrographs would be characterised by steep recession limbs (pers. comm. Smart 1998). Pupu Springs (i.e. Main Springs and Dancing Sands) would run dry if this connection was direct and substantial. However, the variation in total onshore discharge is not great, ranging from 7500-19500 l/s (in large karst systems such as Waikoropupu Springs a range of this magnitude is considered small, pers. comm. Smart 1998). Waikoropupu Springs do not display any steep recession limbs typical of an overflow spring, although the massive scale of the WAM Aquifer could dampen the hydrograph response. The hydrographs display "well behaved recessions", again not characteristic of an overflow system.

3.4 AQUIFER FLUCTUATIONS

3.4.1 Observation wells

Groundwater levels of the WAM Aquifer are monitored by only two wells, Hamama (WWD 6710, N26 921324) and Balls (WWD 6011, N26 902394). Both are fitted with automatic recorders, with readings taken every 15 minutes. For evaluation purposes, only the Balls well record, which extends from June 1994 to the present, will be examined. Balls is located approximately 425 m southwest of Main Springs and about 240 m from Fish Creek Springs. Mueller (1992) gives a detailed evaluation of the Hamama records. Hamama is considered in this thesis to record from an offshoot (or weak link) of the principal drainage arrangement underlying the Takaka River, and is not examined.

Groundwater level fluctuations occur over a wide range of time scales, from minutes to years (Smith and Wheatcraft 1993). It is common to evaluate fluctuations at a number of levels, looking at the following:

- long-term fluctuations, observed over a number of years,
- seasonal fluctuations, observed on an annual basis, and
- short-term fluctuations, which may last only a few minutes, or last several weeks.

The determination of the cause of fluctuations, the magnitude of observed groundwater level changes, and the frequency of such occurrences can all provide useful information on the groundwater system. The Balls recorder represents the part of the WAM Aquifer which is near both Waikoropupu Springs and the coastline. Fluctuation results taken from it are not considered representative of the entire system.

3.4.2 Long term groundwater fluctuations

Long term lowering of the groundwater levels represents a depletion of aquifer storage, and may result from higher groundwater demands compared to recharge, or from net decrease in recharge input (the difference between a wet and a dry year). No overall trends in groundwater levels are obvious from the Balls record, but differences between wet and dry years are evident. Groundwater levels recorded in 1997 are consistently below the mean. Mean annual water levels recorded for 1995, 1996, and 1997 are 19010 mm, 18962 mm, and 17977 mm respectively.

3.4.3 Seasonal groundwater fluctuations

Seasonal groundwater fluctuations typically result in lower summer groundwater levels (as a result of decreased recharge, rainfall, increased evaporation, and abstraction), and higher winter/spring levels (as a result of increased input, and decreased evaporation). Balls record does not display a marked seasonal response; this is shown in the series of hydrographs of 1995, 1996, and 1997 (Figure 3.27 (a)-(c)). Unusually dry winters (e.g. in 1997) and summer storm events interrupt any seasonal trends. It is also likely that the huge storage volume of the WAM Aquifer plays a contributing role in buffering seasonal groundwater level fluctuations.

3.4.4 Short term fluctuations

3.4.4.1 Input events

A) Natural recharge

The response of Balls water level to natural recharge events (i.e. rainfall and Upper Takaka River flow) is variable, and is controlled by the transit time through the aquifer. This time of throughflow is itself a function of conduit geometry, intensity and magnitude of recharge, and antecedent hydrologic and meteorological conditions.

A series of hydrographs for a moderate recharge event (autogenic/allogenic, and diffuse/concentrated) is shown in Figure 3.28; as the primary event was a sharp pulse, these are instructive for analysis. Stable river flow, minimal rainfall, and steadily declining groundwater levels were the conditions 5 days prior to the recharge event.

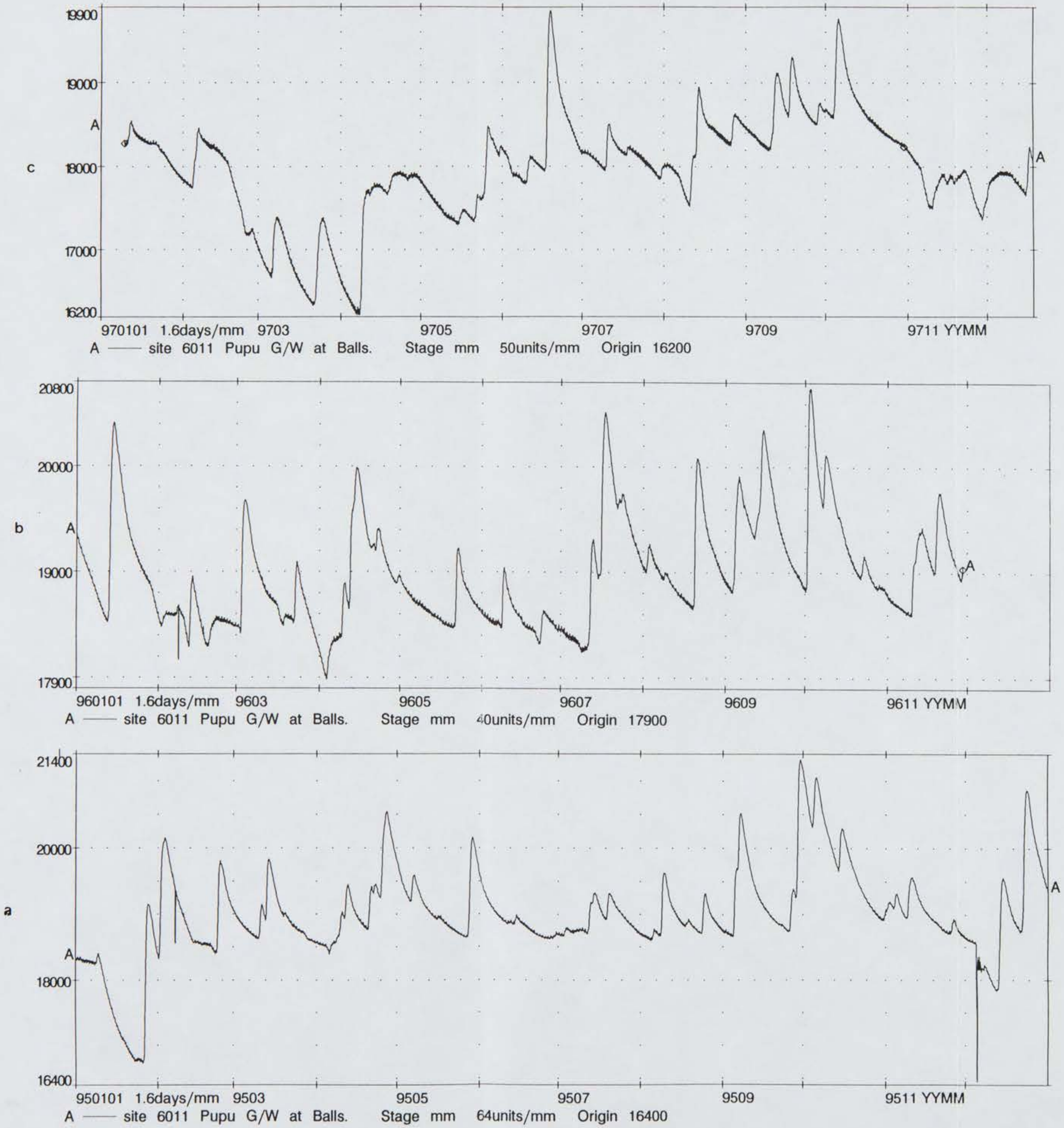


Figure 3.27. Hydrograph record for the Balls water level recorder, 1995, 1996, and 1997. No distinct seasonal trend is apparent.

Specific features shown in Figure 3.28 include an overall rise in groundwater level of the order of 1881 mm. Time to peak groundwater level is approximately 41 hours, and lag time in the peak input vs. peak groundwater level is approximately two days. Initial groundwater response is delayed approximately 4 hours behind the commencement of rise of recharge.

B) Artificial recharge

Artificial recharge inputs derived from Cobb power station generation releases are important short term regulators of aquifer water level. Under low flow regimes (typically of the order of 2000-3000 l/s) the Takaka River is dry around its confluence with the Craigieburn Creek. Additional input (up to a maximum of 7200 l/s) travels down the upper Takaka River channel as a kinematic wave, enters the Takaka recharge zone, and on encountering the phreatic zone of the WAM Aquifer is transmitted as a pressure pulse through the confined aquifer. These pulses register as increases on the Balls water level recorder. An example of groundwater response from an artificial recharge (presented as an over-plot of Balls groundwater and Harwoods flow) is shown in Figure 3.29. Flow in the Upper Takaka River increases from 2300 l/s to 9400 l/s for a period of 15 hours as a result of water releases from the Cobb power station. The resultant change in Balls water level due to the pulse is approximately 36 mm. Rise to peak is approximately 12 hours; recovery from the peak to the pre-event conditions is between 36 and 48 hours. Lag between river peak and water level peak is of the order of 12 hours. Releases from the Cobb power station impact profoundly on the Upper Takaka River regime, the WAM Aquifer water levels, and Waikoropupu Springs discharge.

3.4.4.2 Output events

Short term fluctuations due to artificial abstraction of the Balls bore are recognised in the hydrograph records as a series of pumping spikes. Pumping shown in Figure 3.30 is associated with an decrease in groundwater level of approximately 1300 mm, sustained for a period of 90 minutes. Drawdown in aquifer water level as a result of pumping at Balls is localised. It is thought that pumping of the bore at 10 l/s does not affect Waikoropupu Springs discharge (Thomas 1995).

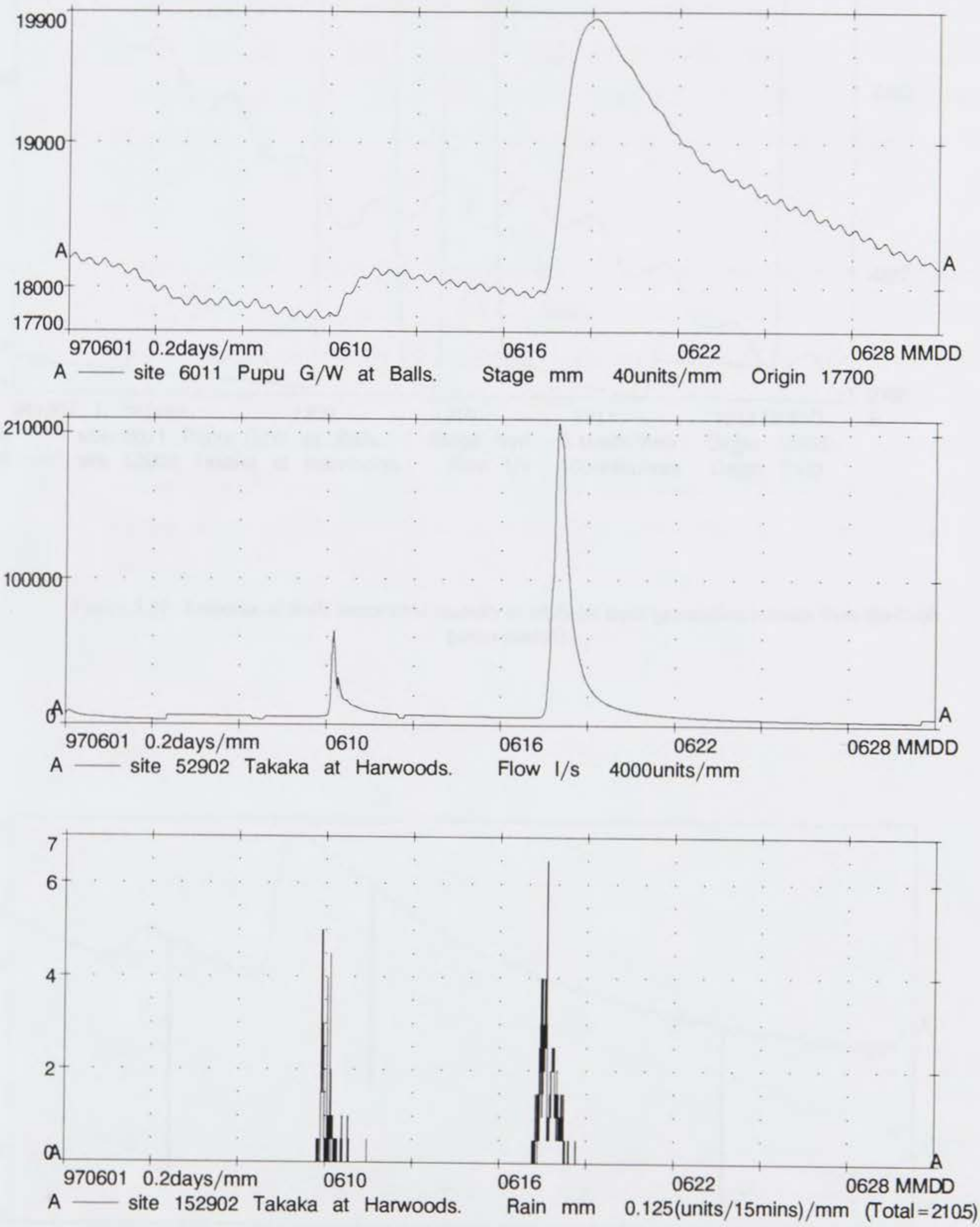


Figure 3.28. Response of Balls water level recorder to natural recharge inputs.

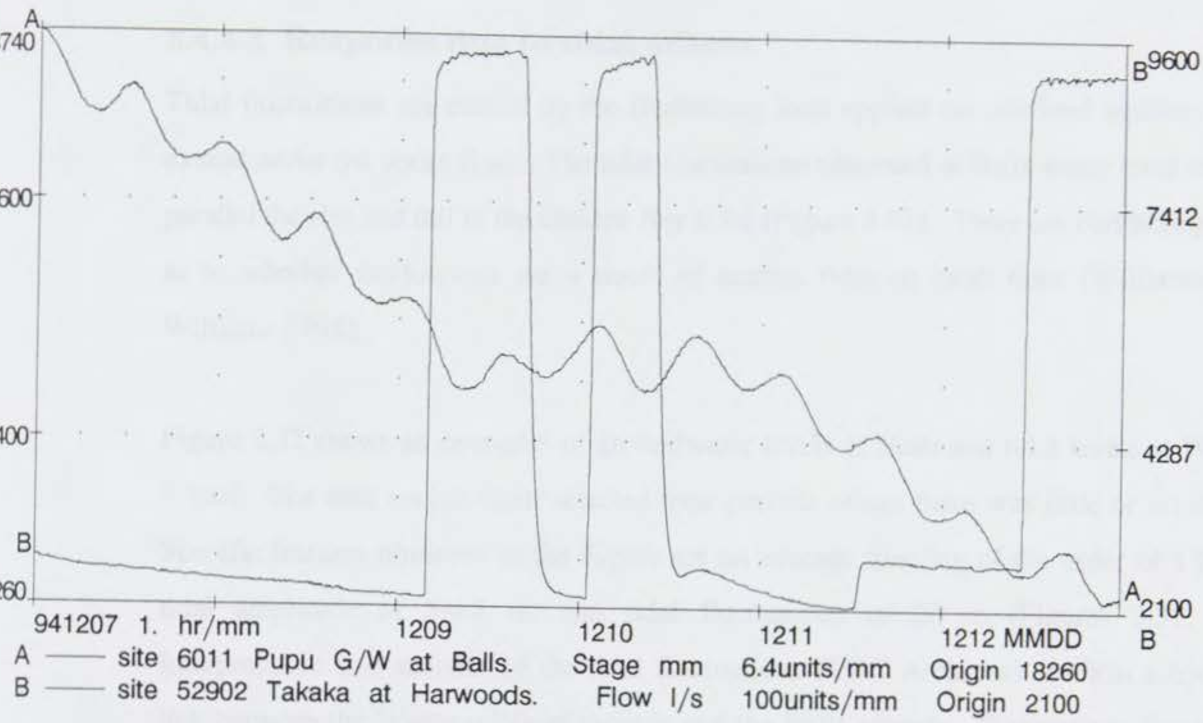


Figure 3.29. Response of Balls water level recorder to artificial input (generation releases from the Cobb power station)

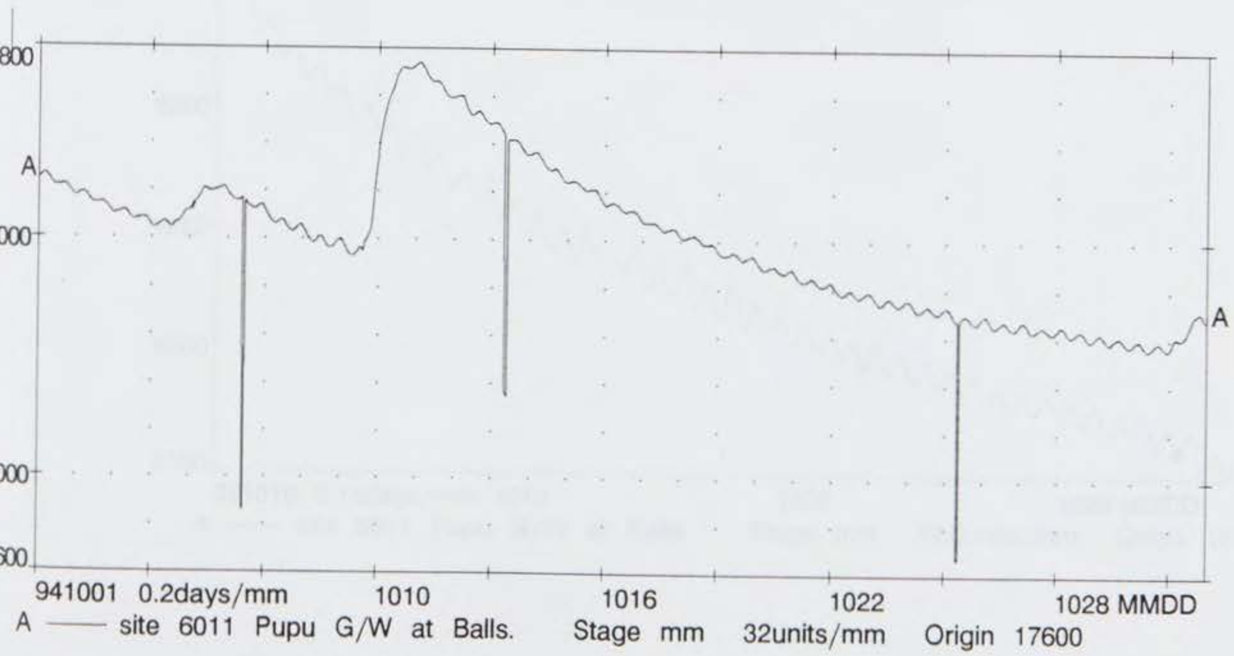


Figure 3.30. Presence of pumping spikes in the Balls water level record

3.4.4.3 Response due to tidal effects

Tidal fluctuations are caused by the fluctuating load applied on confined aquifers which extend under the ocean floor. The tidal fluctuations observed at Balls water level recorder parallel the rise and fall in the Golden Bay tides (Figure 3.31). There are conflicting views as to whether fluctuations are a result of marine tides or earth tides (Williams 1977, Williams 1992).

Figure 3.32 shows an over-plot of groundwater levels at Balls and tidal levels at Waitapu Wharf. The data set has been selected over periods where there was little or no rainfall. Specific features observed in the Figure are an average time lag of the order of 1 hour, a tidal amplitude of 2-4.5 m, and tidal fluctuations of 20 m (Figures 3.31, 3.32). Interpretation and analysis of the tidal fluctuations (TDC Archives) confirm a hydraulic link between the Waitapu Wharf records and the Balls records. Fluctuations due to tidal loading do not necessarily indicate a conduit connection from the onshore springs to offshore.

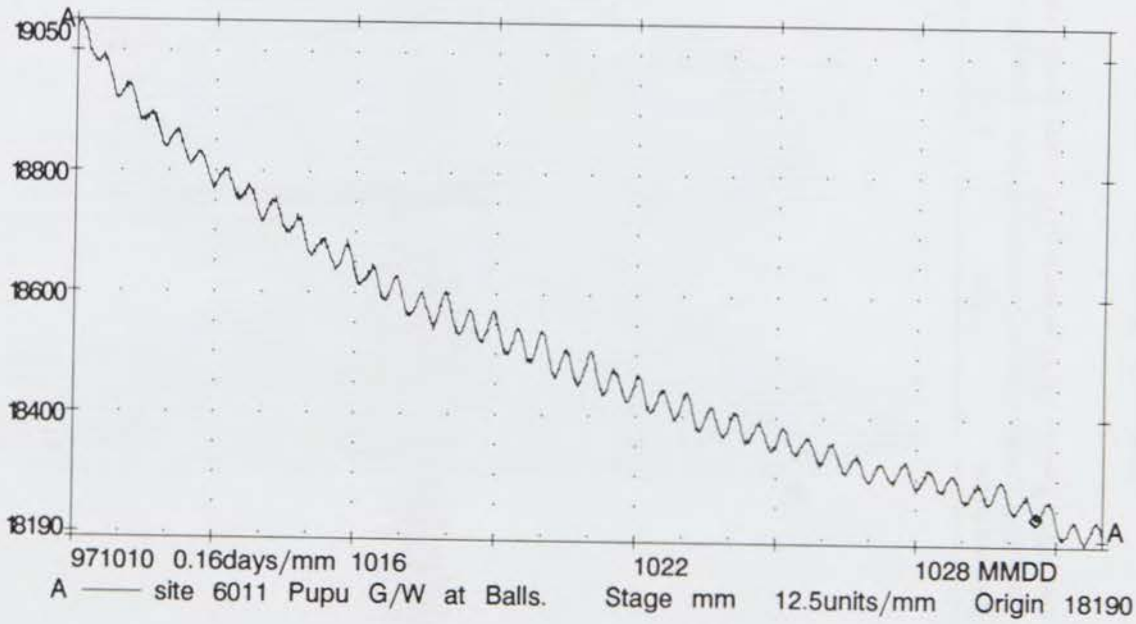


Figure 3.31. Example of typical tidal fluctuations observed in the Balls water level recorder

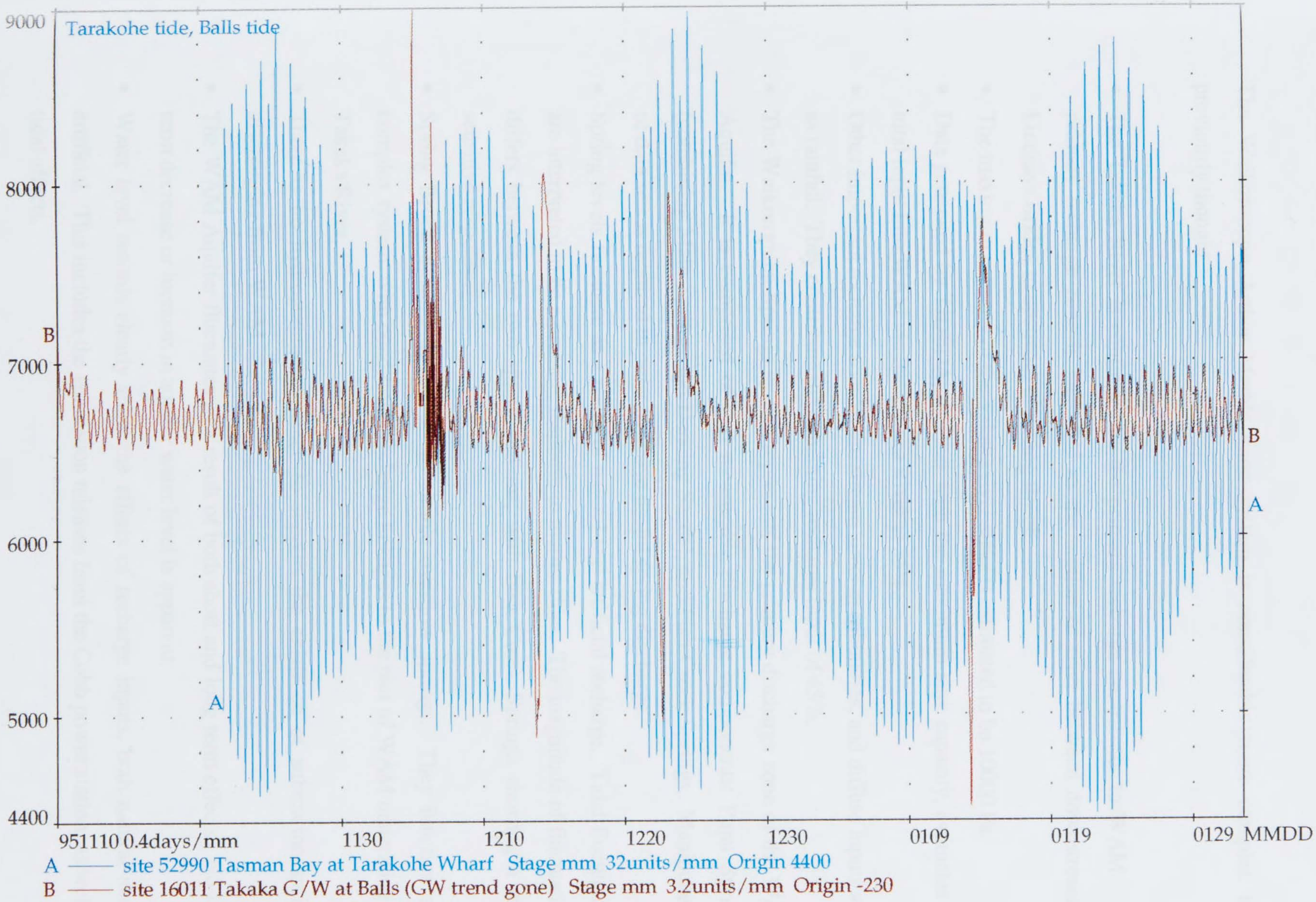


Figure 3.32. Hydrograph overplot of the Balls water level recorder and the Waitapu Wharf tidal recorder

3.5 SYNTHESIS

The Waikoropupu Arthur Marble karst system is considerably more complex than previously thought.

- The Takaka River is confirmed as the primary recharge contributor to WAM. The primary recharge zone is identified as the section of river between downstream of Lindsays Bridge to upstream of Spring Brook.
- The maximum capacity of the Takaka river sinks is estimated to be 10000 l/s.
- Data generated by TIDEDA, together with the maximum sink capacity, estimates the total input into WAM via the Takaka River at 55%.
- Other important recharge sources are stream sinks in tributaries, and diffuse inputs such as rainfall. They contribute the remaining recharge input of 45%.
- The Waikoropupu Springs system represents the primary discharge zone of the WAM Aquifer. It is comprised of two measurable discharge components: Pupu Springs (combining Main Springs and Dancing Sands), and Fish Creek Springs. Manipulation of data sets is required in order to derive useful spring discharge.
- Spring levels fluctuate as a result of natural and artificial recharge. Tidal fluctuations are interpreted to be a pressure response to marine tides. The magnitude of fluctuations differs between the two spring systems, with Fish Creek Springs showing a more sensitive response.
- Spring Brook Springs do not act as simple overflow springs. They function as a complex system, with conditional recharge linkages to the part of WAM underlying the Takaka River.
- There is no hydrographic evidence to support the existence of submarine springs discharging from WAM.
- The WAM Aquifer fluctuates as a result of both short and long term effects. No long term decrease or increase in aquifer water level is apparent.
- Water level records clearly show the effects of recharge inputs, both natural and/or artificial. This includes the generation releases from the Cobb power station, as well as tidal effects.

- A record of WAM spring discharge which is not generated from Balls is required, in order to provide more robust data.
- A monitoring bore located in the Takaka River recharge zone is essential if recharge processes are to be further quantified.

The interpretation of the WAM Aquifer system in this thesis is based on information available at the time of writing. Future borehole placements or installation of new water level or discharge recording sites may alter future interpretations.

CHAPTER FOUR : HYDROGEOLOGY OF THE LIMESTONE AND GRAVEL AQUIFERS OF EAST TAKAKA AND TAKAKA TOWNSHIP

4.1 INTRODUCTION

The purpose of this chapter is to give a general account of the hydrogeological features of the limestone and gravel aquifers of East Takaka and Takaka Township. These areas are selected because of the importance of water resource management issues and because of the relevance of water quantity and quality understanding to groundwater management. Only limited hydrogeological information exists for the limestone and gravel aquifers, and little previous work has been done (Stewart and Williams 1981, Mueller 1992, 1987).

The aquifers studied are the minor karst East Takaka-Motupipi Limestone Aquifer (ETML), and the gravel aquifers known as the Takaka Township Gravel Aquifer (TTG) and the East Takaka Gravel Aquifer (ETG). Discussions in this chapter cover the following:

- the identification of sources and sites of recharge, with estimation of contribution where possible,
- the identification of discharge zones, which for all aquifers under discussion is descriptive rather than quantitative (due to lack of hydrological data),
- the evaluation of groundwater flow in the aquifers by measurement of water elevations in suitable wells, in order to construct potentiometric contour maps, and
- the assessment of groundwater fluctuations, with quantification restricted only to the ETML aquifer.

Water chemistry of all three aquifers is presented in Chapter Five, while general details of aquifer boundary conditions are given in detail in Chapter Two.

Discussion of the water table fluctuations in the two gravel aquifers uses the writer's own measurements, together with verbally reported observations of local landowners. Suggestions are made for future work, and the establishment of an improved monitoring network is proposed, in order to improve the understanding of the minor aquifer systems in the Takaka Catchment

4.2 THE EAST TAKAKA-MOTUPIPI LIMESTONE AQUIFER

4.2.1 Aquifer description

The East Takaka-Motupipi Limestone Aquifer (ETML) is the minor karst aquifer in the Takaka Valley. It covers 43 km^2 and extends from East Takaka to the Golden Bay coast. It is structurally complex, and a number of major and minor folds and fault structures have been mapped (Figures 2.5, 2.6, Grindley 1971, Judd 1989). For water resource management of the ETML Aquifer, it is necessary to subdivide its areal extent into a number of sub-aquifers. This subdivision is based on structural surface mapping (Judd 1989, Grindley 1971). Further investigation is required to clarify the subdivision in a hydrogeological sense, i.e. to ascertain whether the sub-aquifers function and respond as isolated or semi-isolated systems.

The proposed subdivision is as follows:

- The East Takaka sub-aquifer is bounded to the east by the Pikikiruna Fault, and has an approximate western boundary marked in Figure 4.1. The northern extent is located near the quarry (N26 954353), and the southern extent is near Gorge Creek. A major fold structure has been mapped (Grindley 1971, Judd 1989), and the presence of the East Takaka Fault system is assumed (details of which are given in section 2.3.2.2).

- The Central Takaka-Motupipi sub-aquifer covers an area bounded by the Pikikiruna Fault in the east, with the most likely western boundary shown in Figure 4.1. Several prominent folds have been mapped, along with some minor ones (Grindley 1971, Judd 1989). Judd (1989) interpreted the blind thrust underneath Trig DD (Figure 2.6) as the division between the north-western and north-eastern major folds.

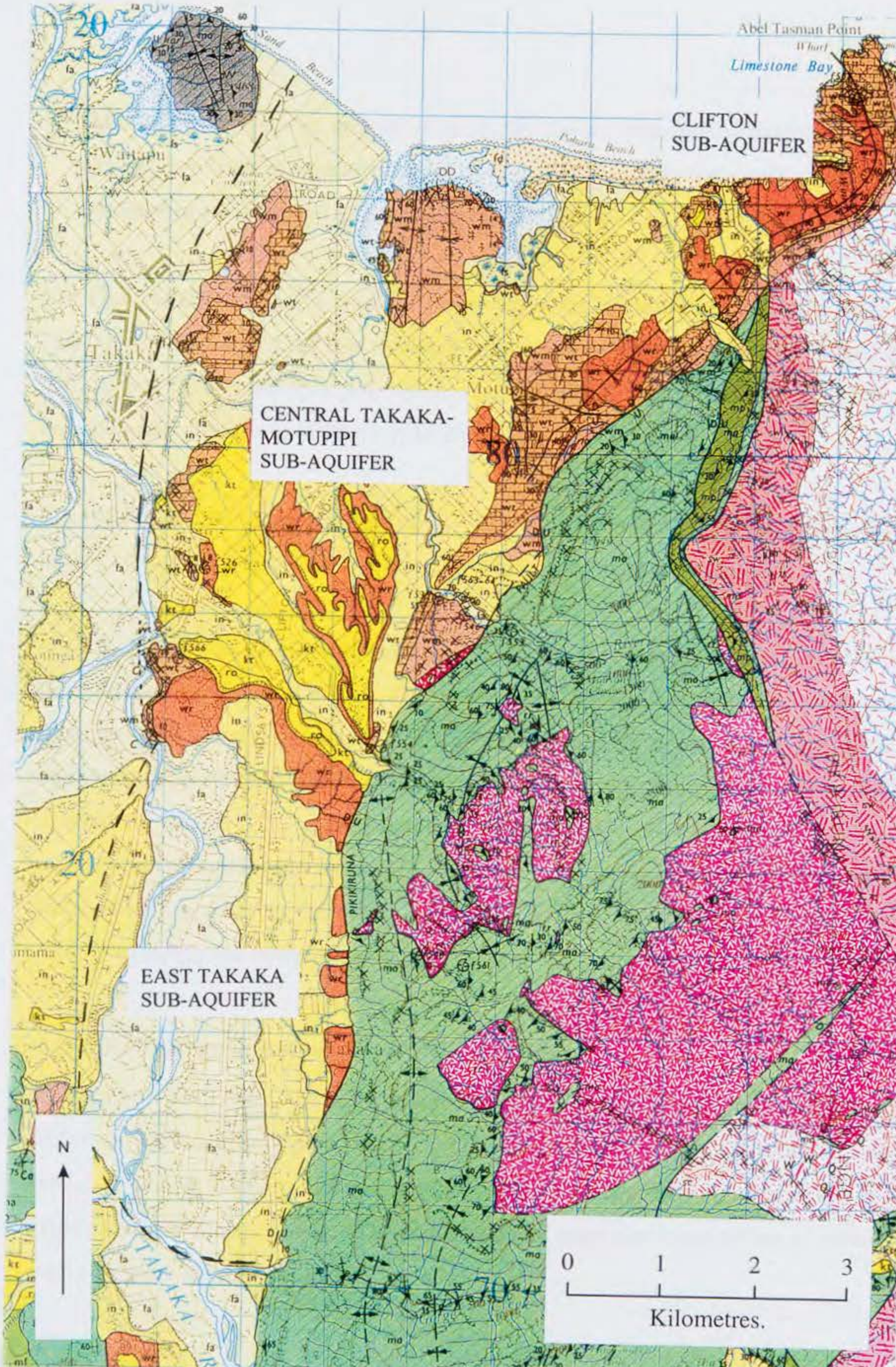


Figure 4.1. Sub-aquifers in the East Takaka-Motupipi Limestone Aquifer
(Map taken from Sheet S8, Grindley 1971)
Stratigraphic information given in Figure 2.1

- The Clifton sub-aquifer (Figure 4.1) is the most north-eastern extension of the Motupipi syncline; the greater part of this aquifer, however, lies outside the Takaka Catchment boundary, and will not be discussed further.

The East Takaka sub-aquifer could be connected to the Central-Motupipi sub-aquifer, as Judd (1989) has marked the fold structures as continuous down the extent of the valley. The Central Takaka-Motupipi sub-aquifer could also be further subdivided, based on the the existence of complex folding and faulting.

The following discussions use the term ETML Aquifer when referring to the total extent of the limestone aquifer. Sub-aquifers are referred to by their individual names.

In total, 35 bores and wells encounter the ETML aquifer (based on the Tasman District Council Well Archives). Of these, 30 tap the Central Takaka-Motupipi sub-aquifer, and 5 tap the East Takaka sub-aquifer. Water use is primarily domestic and agricultural. Further use of the ETML aquifer is likely to occur, as a result of a general increase in the demand for water. The gravel aquifers (which provide an alternative groundwater resource in the region) are inherently unreliable, and during extended dry periods the wells which tap them are known to run dry. This puts added pressure on the ETML Aquifer to supply the needs of the region.

4.2.2 Recharge sources the ETML Aquifer

Recharge of the ETML Aquifer is comprised of autogenic and allogenic components, which are derived from distinct sources. This is in direct comparison to the recharge inputs of WAM (section 3.2) and the Quaternary Gravel aquifers (sections 4.3, 4.4) (Stewart and Williams 1981). The importance of particular components of recharge varies between the sub-aquifers.

Recharge sources, together with the sub-aquifer directly affected, are as follows:

1. Low altitude diffuse autogenic rainfall falls directly on, and infiltrates into, the Takaka Limestone cropping out at the foot of the Pikikiruna Scarp (Stewart and Williams 1981). It is an important recharge source for the Central Takaka-Motupipi sub-aquifer.

2. Concentrated allogenic inputs contribute along the eastern boundary of the entire ETML Aquifer via the Pikikiruna Fault.

3. Diffuse allogenic rainfall input percolates through the permeable gravels into the Takaka Limestone in areas where Tarakohe Mudstone is not present. In such areas there is a direct connection between the gravels and the limestone. In areas of Motupipi it may be an important localised component of recharge; borehole evidence in these areas show gravels unconformably overlying Takaka Limestone.

4. Concentrated allogenic inputs contribute via the stream sinks located in the Dry River (Mueller 1992) and Rameka Creek. These are important recharge sources for the Central Takaka-Motupipi sub-aquifer.

5. The Takaka River is an important concentrated allogenic recharge source for the East Takaka sub-aquifer. The Pikikiruna Fault may provide an avenue for water movement.

6. Potential inter-aquifer leakage and/or recharge from the underlying WAM Aquifer (Ravens 1990, Judd 1989) may occur via the East Takaka Fault system. This would particularly affect the East Takaka sub-aquifer.

The diffuse autogenic recharge contribution to the Central Takaka-Motupipi sub-aquifer is estimated based on a limestone outcrop exposure of approximately 3.5 km^2, a mean annual rainfall of 2600 mm (Appendix D-II), and an estimated infiltration percentage of 70%. The infiltration figure was based on previous karst recharge investigations by

Milanovic 1981. Recharge via diffuse precipitation is estimated at 637×10^5 m^3yr^{-1} (the equivalent of 0.2 m^3s^{-1}).

Sink zones coincide with Takaka Limestone exposure, as shown in Figure 4.1. Increased borehole water levels (of variable magnitudes) have been observed in WWD 6405 directly after runoff events in Rameka Creek (pers. comm. Packard 1997). Quantification of stream sink contribution has not been attempted.

It is assumed that a faulted connection exists between the Takaka Limestone and Arthur Marble through the East Takaka Fault system (section 2.3.2.2, Ravens 1990). Quantification of potential inter-aquifer recharge is impossible at the time of writing, because of the lack of borehole control.

4.2.3 Discharge sites of the ETML Aquifer

The ETML discharge sites are discussed in terms of the sub-aquifers.

The principal discharge zone of the East Takaka sub-aquifer is East Takaka Springs, which is comprised of numerous minor springs. The extent of East Takaka Springs is shown in Figure 1.7. They discharge via a number of minor intermittent streams into the Takaka River approximately 300 m upstream of the Paynes Ford Bridge. Available gaugings show spring discharge ranging from 82 l/s to 287 l/s (Appendix C-II). Discharge increases appreciably after rainfall events.

The principal discharge sites of the Central Takaka-Motupipi sub-aquifer are Motupipi Springs (N26 946389) and the numerous small springs which discharge into the Motupipi River (Figure 1.7). All are ephemeral in nature. Submarine discharge issuing from Takaka Limestone at the northern extent of the Central Takaka-Motupipi sub-aquifer was suspected by Mueller (1992); however, no vents have been located.

No continuous monitoring of any ETML discharge sites occurs. The unknown component of discharge issuing from the whole ETML system hinders any further water balance or budget analysis.

4.2.4 Groundwater fluctuations of the ETML Aquifer

4.2.4.1 Observation wells

Groundwater records exist for one long term and three short term monitoring bores which tap the ETML Aquifer (Figure 1.12). Only two sites are presently operating, namely the C'Serneys recorder located in the Central Takaka-Motupipi sub-aquifer, and the Jeffersons recorder located in the East Takaka sub-aquifer. C'Serneys is situated between the Motupipi River and Kite Te Tahu Creek at N26 970390. Drilled to a depth of 45.7 m, it was installed as part of a short term monitoring programme to investigate the response of the Takaka Limestone groundwater levels. Jeffersons bore (N26 942309), situated in close proximity to the Takaka River, provides a short term water level record for the East Takaka sub-aquifer (Figure 1.12). This well (21 m deep) is confirmed to tap limestone (as opposed to marble) by this writer's analysis of drill chip samples. Additional water level fluctuation is available from the short term records of Grove Orchard and Jardines (Figure 1.12). Details of all monitoring bores are presented in Appendix B.

4.2.4.2 Long term fluctuations

In the C'Serneys records for 1990 to 1997 there is no obvious increase or decrease in general groundwater levels in the Central Takaka-Motupipi sub-aquifer. This suggests that over the long term the demands and outputs from this subsystem of the ETML Aquifer are equal to the groundwater recharge. There are differences, however, between dry and wet (or wetter) years. 1997 monthly water level means for the C'serneys recorder are consistently low (compared with the mean of 12219 mm above msl). February, March, and April monthly means are 10352 mm, 9527 mm, and 8824 mm respectively. Water levels during June 1997 are the lowest recorded (with the minimum of 8105 mm recorded on 16 June). Reduced rainfall recharge is a contributing factor; the total rainfall for 1997 at the Kotinga station is 1284 mm, compared with 2628 mm and 2210 mm for 1995 and 1996 respectively.

A long term evaluation of the Jeffersons record is not appropriate, due to the short length of the data set available. Summary statistics for 3 selected sites are given in Table 4.1.

Table 4.1. Summary statistics for water levels measured at 3 sites in the ETML Aquifer, with the appropriate sub-aquifer in parentheses. Units are mm above msl. Date time format is yymmdd.

Site	Maximum and Date	Minimum and Date	Mean	Standard Deviation	Dates of Record
C'serneys (Central-Motupipi)	16822 on 890714	8105 on 970616	12219	1833	900101-971030
Jeffersons (East Takaka)	33548 on 980523	30746 on 980328	31995	429	980301-980623
Grove Orchard (Central-Motupipi)	36606 on 951010	27910 on 960227	32442	1292	950811-970423

4.2.4.3 Seasonal fluctuations

Mean monthly borehole water levels for the C'Serneys recorder for 1995, 1996, and 1997 are presented in Table 4.2. Elevated groundwater levels (higher than the mean of 12219 mm above msl) are recorded in the months of June, July, August, September, and October (Table 4.2). Seasonal groundwater level variation for 1995 is shown in Figure 4.2. Water levels are lower during the summer months of January to March. There is an increase or winter recovery during July and August. This appears to be a typical seasonal pattern.

In summer (particularly from December to March) there is lower than mean rainfall. Records for January 1997 assume increased summer groundwater abstraction, and increased evaporation. In winter, particularly in the months of July to September, there is increased recharge, reduced evaporation, and reduced abstraction. A comparison of the 1996 record of C'Serneys with the rainfall record of Kotinga (a representative mid-Takaka Valley station) is given in Figure 4.3. Groundwater levels at C'Serneys are loosely correlated with Kotinga rainfall.

GROUNDWATER LEVELS FOR THE C'SERNEYS RECORDER 1995-1997												
	January	February	March	April	May	June	July	August	September	October	November	December
1995	11810	12420	12480	12720	13180	13370	13390	13520	14150	15620	14810	13390
1996	13380	12330	11970	12880	13430	12750	12690	14140	14550	14600	13760	13130
1997	11460	10350	9530	8820	8310	8580	10000	10730	11840	na	na	na

na = not available

Table 4.2. Monthly mean water levels for the C'Serneys water level recorder. (Figures are quoted in mm above msl)

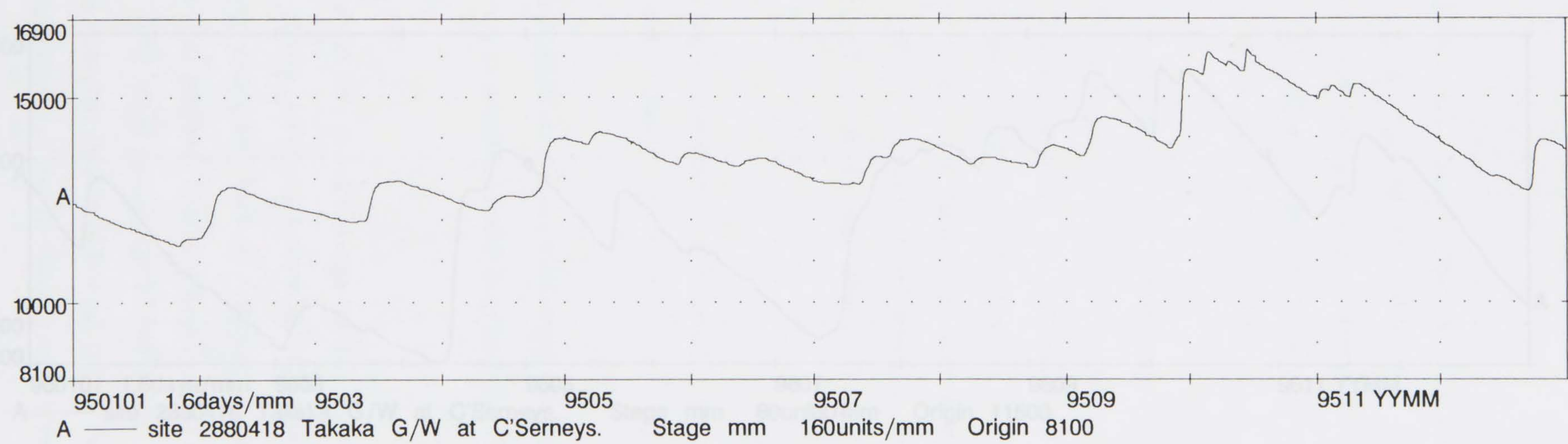


Figure 4.2. Hydrograph record of the C'Serneys monitoring bore for 1995. Distinct seasonal fluctuations are observed.

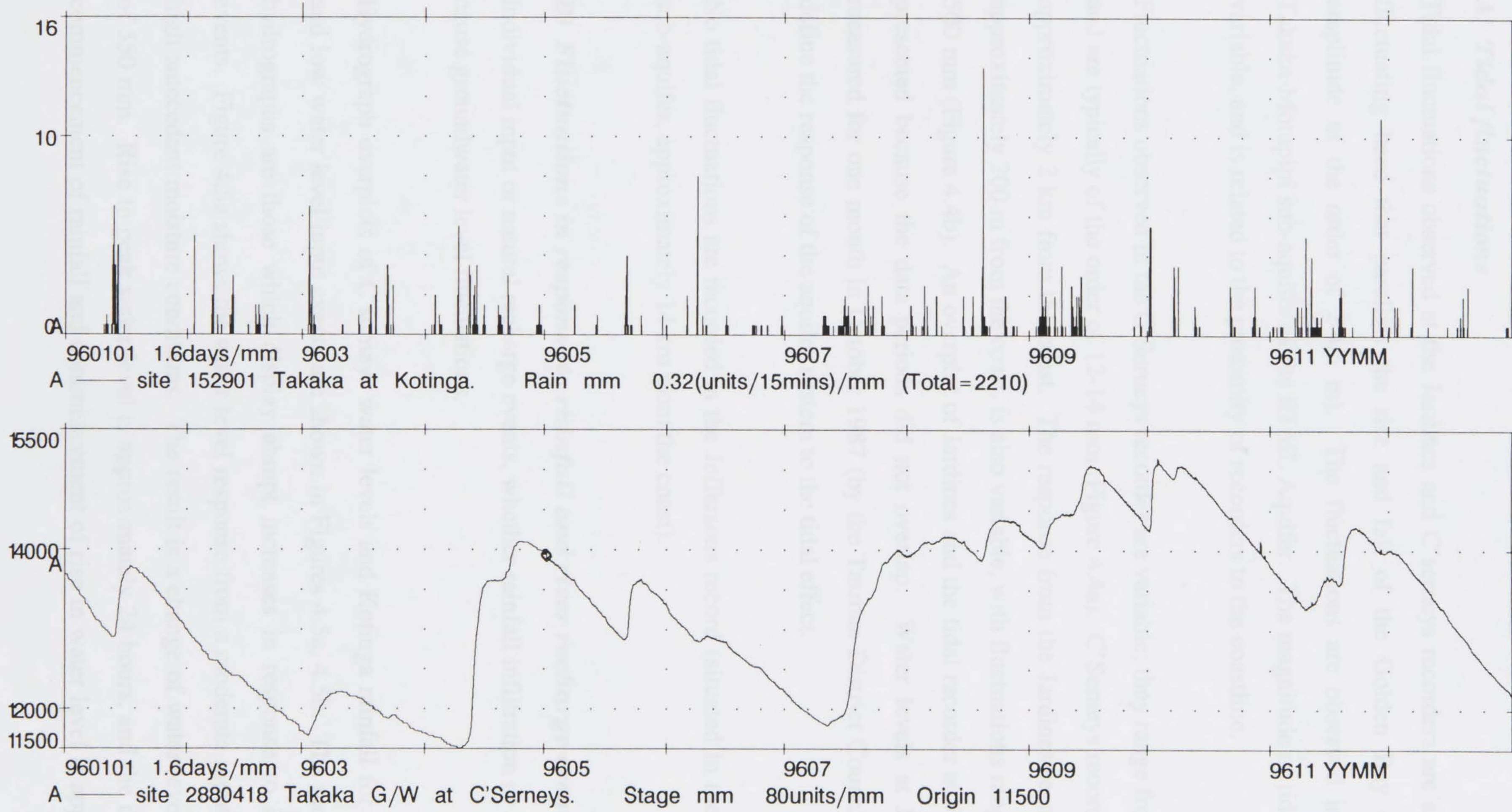


Figure 4.3. Hydrograph plots of C'Serneys water level record and Kotinga rainfall station (1995)

4.2.4.4 Short term fluctuations

A) Tidal fluctuations

Tidal fluctuations observed at the Jardines and C'serneys recorders are a result of the fluctuating head that parallels the rise and fall of the Golden Bay tides (typical amplitude of the order of 2-4.5 m). The fluctuations are observed in the Central Takaka-Motupipi sub-aquifer of the ETML Aquifer. The magnitude of tidal response is variable, and is related to the proximity of recorders to the coastline.

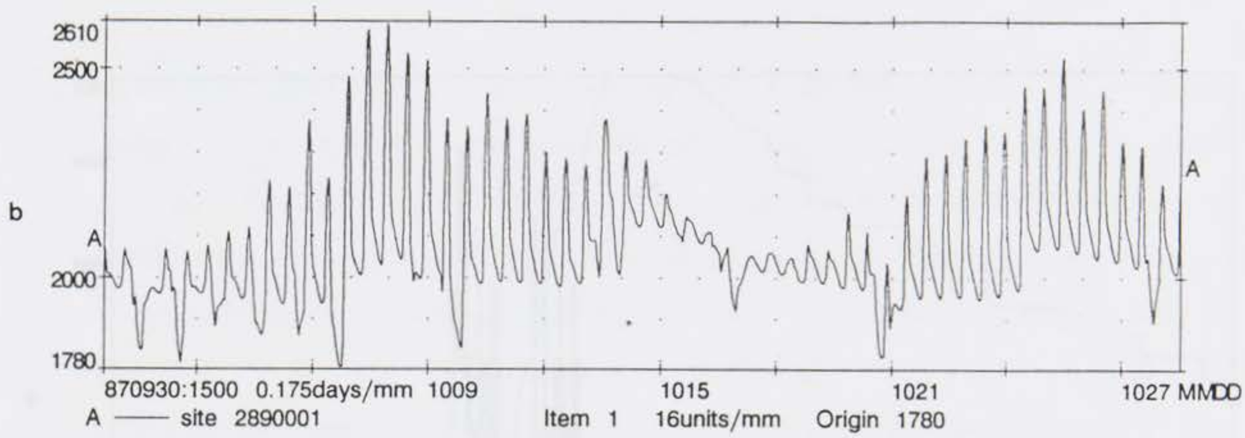
Fluctuations observed in the C'Serneys recorder are variable; they range from 10-30 mm and are typically of the order of 12-14 mm (Figure 4.4a). C'Serneys recorder is situated approximately 2 km from the coast. The response from the Jardines recorder, situated approximately 200 m from the coast, is also variable, with fluctuations ranging from 50-500 mm (Figure 4.4b). An overplot of Jardines and the tidal recorder at Waitapu is not presented because the data periods did not overlap. Water levels at Jardines were measured for one month in October 1987 (by the Tasman District Council) in order to define the response of the aquifer system to the tidal effect.

No tidal fluctuations are recorded in the Jeffersons record (situated in the East Takaka sub-aquifer, approximately 14 km from the coast).

B) Fluctuations in response to rainfall and river recharge events

Individual input or natural recharge events, whether rainfall infiltration or river leakage, cause groundwater level fluctuations.

Hydrograph overplots of C'serneys water levels and Kotinga rainfall for selected high and low water level input events are shown in Figures 4.5a, 4.5b. The most instructive hydrographs are those which display abrupt increases in response to isolated input events. Figure 4.5a shows the water level response from a moderate input event during high antecedent moisture conditions. The result is a change of water level of the order of 550 mm. Rise to peak water level is approximately 24 hours, and the delay between commencement of rainfall and commencement of rise in water level is approximately 6



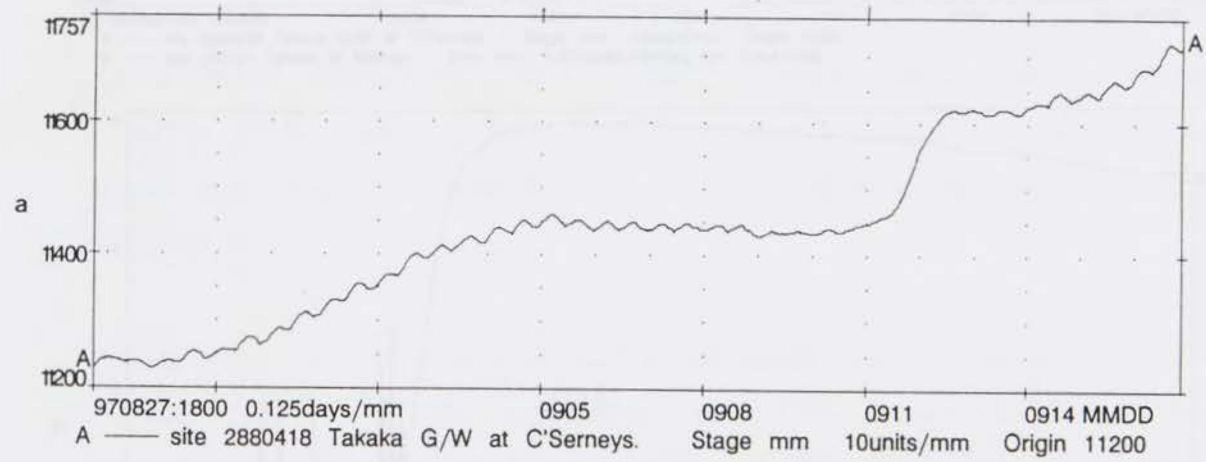


Figure 4.4a and b. Tidal responses for the C'Serneys and Jardines water level recorders

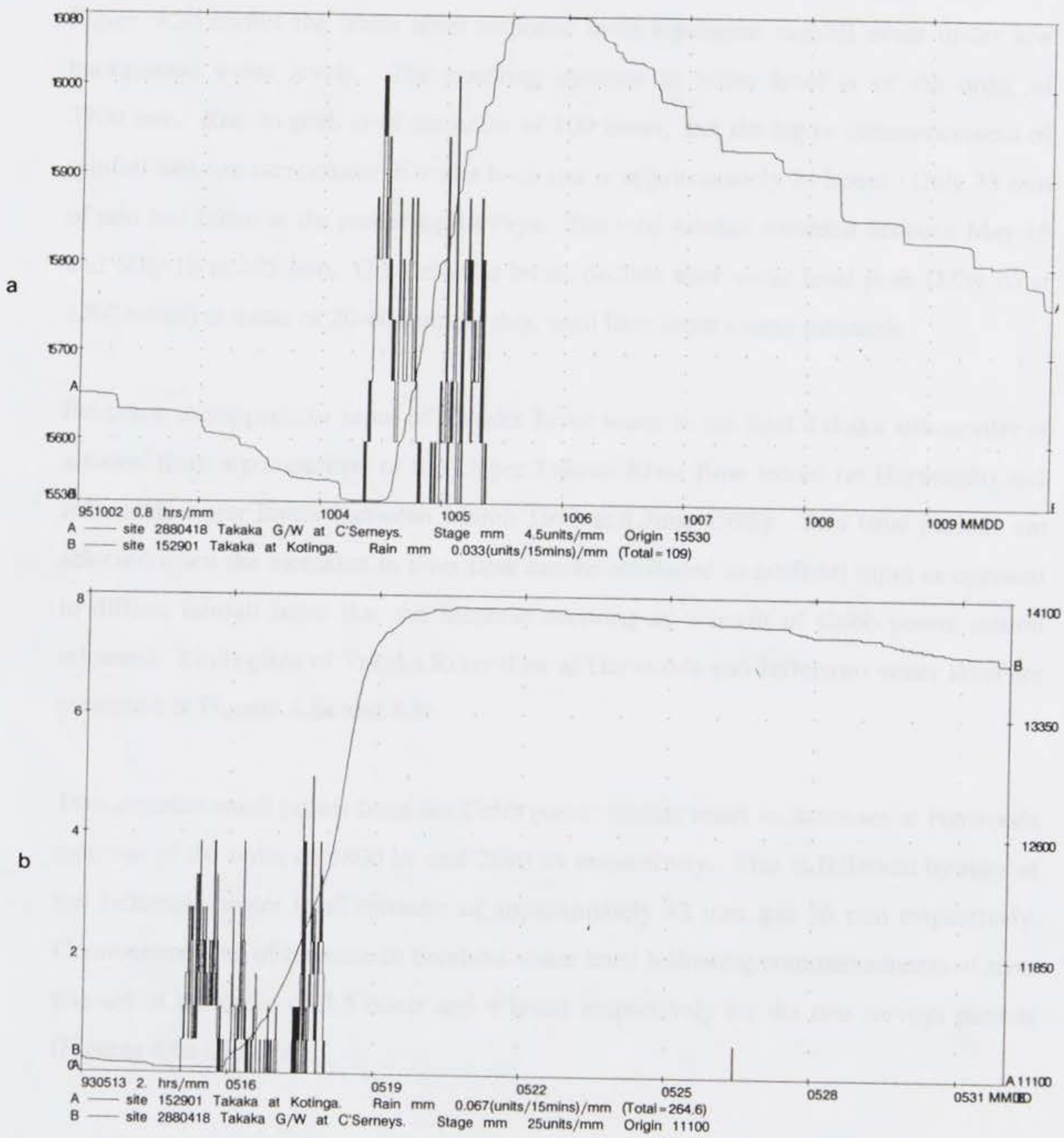


Figure 4.5a and b. Response of C'Serneys water level recorder to natural recharge. Figure a is an example of high background water levels, Figure b is an example of low background water levels.

hours. The total rainfall for the recharge event as measured at Kotinga is 109 mm, and the total rainfall for the preceding 14 days is approximately 200 mm.

Figure 4.5b shows the water level response from a selected rainfall event under low background water levels. The resulting increase in water level is of the order of 2900 mm. Rise to peak is of the order of 109 hours, and the lag in commencement of rainfall and commencement of water level rise is approximately 24 hours. Only 33 mm of rain had fallen in the preceding 14 days. The total rainfall recorded between May 15 and May 18 is 265 mm. Groundwater levels decline after water level peak (May 20 at 1200 hours) at a rate of 20-60 mm per day, until later input events intercede.

Evidence to support the input of Takaka River water to the East Takaka sub-aquifer is gleaned from a comparison of the Upper Takaka River flow record (at Harwoods) and Jeffersons water levels (between March 1998 and June 1998). Two time periods are selected when the increases in river flow can be attributed to artificial input as opposed to diffuse rainfall input (i.e. the increase occuring as a result of Cobb power station releases). Multi-plots of Takaka River flow at Harwoods and Jeffersons water level are presented in Figures 4.6a and 4.6b.

Two separate small pulses from the Cobb power station result in increases at Harwoods recorder of the order of 1800 l/s and 2890 l/s respectively. This is followed by rises at the Jeffersons water level recorder of approximately 42 mm and 36 mm respectively. Commencements of increase in borehole water level following commencements of river rise are of the order of 3.5 hours and 4 hours respectively for the two surveys periods (Figures 4.6a and 4.6b).

C) Atmospheric pressure and loading fluctuations

Barometric pressure data is not available for the Takaka Valley, hence analysis of groundwater fluctuations in response to variations of atmospheric pressure cannot be performed. Changes in barometric pressure are assumed to have some effect on the ETML Aquifer. Recent papers highlight the influence of pressure changes in the analysis of groundwater level time series data. (Bardsley and Campbell 1995, Rasmussen and Crawford 1997)

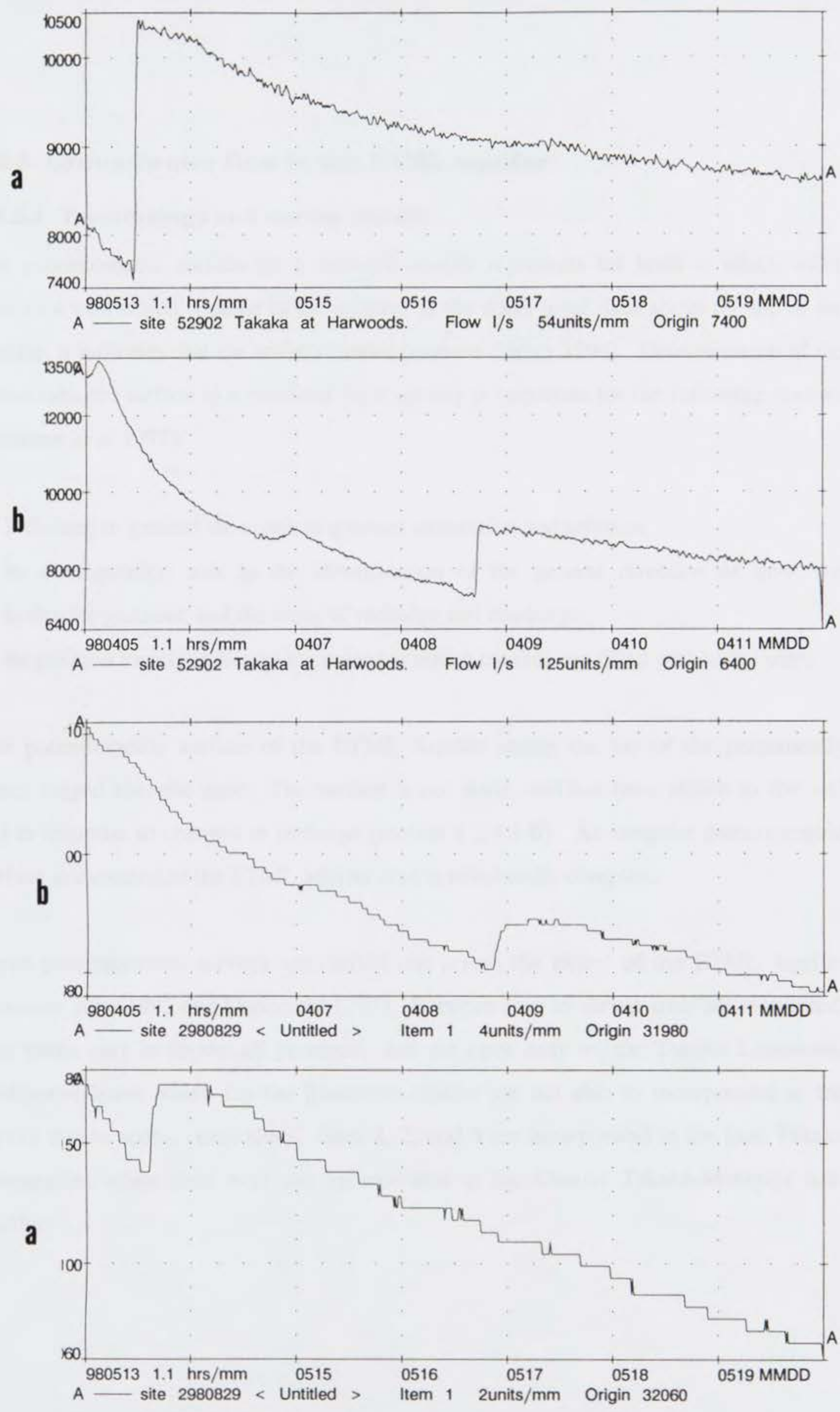


Figure 4.6a and b. Response of Jeffersons water level recorder to artificial inputs (Cobb power station generation releases).

4.2.5 Groundwater flow in the ETML aquifer

4.2.5.1 Terminology and survey details

The potentiometric surface for a confined aquifer represents the level to which water rises in a well which is cased to the aquifer. If the water level rises above the top of the aquifer, it indicates that the water is under pressure (Fetter 1994). Determination of the potentiometric surface in a confined karst aquifer is important for the following reasons (Soliman *et al* 1997):

- It defines in general the zones of greatest circulation and solution.
- Its configuration aids in the identification of the general direction of flow, the hydraulic gradient, and the areas of recharge and discharge.
- Its position locally indicates the extent to which caverns are filled with air or water.

The potentiometric surface of the ETML Aquifer marks the top of the permanently water logged phreatic zone. The surface is not static, and has been shown to rise and fall in response to changes in recharge (section 4.2.4.4.B). An irregular potentiometric surface is expected,as the ETML aquifer area is structurally complex.

Three potentiometric surveys are carried out across the extent of the ETML Aquifer (between June 1997 and December 1997). Between four to eleven sites are monitored. The bores vary in depth; all penetrate, and are open only to, the Takaka Limestone. Additional bores which tap the limestone aquifer are not able to incorporated in the survey due to access restrictions. Sites 1, 2, and 3 are incorporated in the East Takaka sub-aquifer, while sites 4-11 are incorporated in the Central Takaka-Motupipi sub-aquifer.

4.2.5.2 Potentiometric survey results

The reduced level water level (RLWL) with respect to mean sea level for each bore is listed in Appendix G-I. Potentiometric contour maps for the sub-aquifers of the ETML Aquifer are not able to be constructed, due to insufficient geologic, hydrogeologic, and structural controls, and lack of data points. Water levels for each survey are presented in Table 4.3. These provide an indicative picture of the likely flow patterns, directions of flow, and relationship between monitoring sites of the different sub-aquifers.

4.2.5.3 Groundwater flow interpretation

Interpretation of the potentiometric results are as follows:

- The general groundwater flow trend in the East Takaka sub-aquifer is north. The general flow in the Central Takaka-Motupipi sub-aquifer is north to northeast (Figure 4.1).
- Variation of 2.5 m in potentiometric head is noted at the East Takaka sites 1 and 2, while variation of 1.2 m is noted at site 3. The survey results (A-C) are reasonably consistent.
- Variation of 0.7 m in potentiometric head is observed at site 4 (Paynes Ford) between surveys A and C. This section of the Central Takaka-Motupipi sub-aquifer is unlikely to be affected by recharge from the Takaka River.
- Sites 5, 6, 7, 8 and 9, and 10 record similar levels in survey B. In survey C, site 5 records a considerable higher level than other proximal bores. This is assumed to be a result of technical failure of the water probe.

In conclusion, quantitative analysis of flow in the ETML Aquifer or its sub-aquifers is difficult. It is likely that geology, karstification and tectonic setting exert controls over hydraulic connections that are not fully understood.

1997 ETML AQUIFER POTENTIOMENTRIC SURVEYS - 1997					
SITE NO	GRID REFERENCE	WWD	12-Jun	16-Sep	12-Dec
1	N26 951303	6814	32.72	35.06	32.51
2	N26 950305	6821	31.89	33.95	31.49
3	N26 955320	6808	27.05	28.19	27.02
4	N26 944359	6604	21.19	21.89	21.27
5	N26 974377	6405	10.07	18.06	ns
6	N26 972379	6409	10.02	14.81	ns
7	N26 972383	6410	10.64	10.87	ns
8	N26 977384	6411	10.39	ns	ns
9	N26 972389	6419	7.49	10.23	ns
10	N26 970390	6418	8.14	11.70	ns

ns = not surveyed

Table 4.3. Potentiometric results for the East Takaka-Motupipi Limestone Aquifer

4.3 THE TAKAKA TOWNSHIP GRAVEL AQUIFER

4.3.1 Aquifer description

The Takaka Township gravel Aquifer (TTG) is the most important of the Quaternary gravel aquifer in the Takaka Valley. For the purposes of this study the boundaries of the TTG Aquifer are shown in Figure 2.11, and represent a 20 km^2 area of recent alluvium. The TTG aquifer is comprised of a variable thickness of gravel deposits (ranging from 5-32 m) with numerous high yielding water zones. The shallow aquifer is presently being exploited for domestic, agricultural, and industrial use. 21 shallow gravel wells, numerous monitoring wells, and fire hydrants are listed in the Tasman District Council Well Archive database. The TTG provides for and is critically important to the Takaka Township (which has a population of 1664, based on 1996 census results).

4.3.2 Recharge sources of the TTG Aquifer

The primary recharge sources of the TTG Aquifer are as follows:

1. diffuse precipitation input, which falls directly on and infiltrates gravel deposits,
2. input from the Lower Takaka River (from downstream of the Waingaro River-Takaka River confluence to the Anatoki River-Takaka River confluence),and
3. input from the Motupipi River (between the upper reaches and Windles Bridge).

A gross estimate for diffuse rainfall contribution, based on an average rainfall of 2600 $mmyr^{-1}$, a total aquifer extent of 20.1 km^2, and an assumed infiltration capacity of 50 %, is 0.8 m^3s^{-1}, or 261×100000 m^3yr^{-1}.

Previous recharge analysis suggests that the Lower Takaka River recharge (which represents combined flow from the Waingaro, Anatoki and Takaka Rivers) is dominant (Stewart and Williams 1981), and contributes up to 90% of recharge (Mueller 1987). Actual river contribution is difficult to quantify, and would vary considerably according to river levels, antecedent conditions, aquifer storage, and proximity of aquifer areas of interest to the river.

Limited useful gauging data is available to estimate the Lower Takaka River recharge contribution (Appendix C-II). A survey in March 1998, conducted by the writer, selected three suitable sites for gauging (Sites 1-t to 3-t) These are shown in Figure 1.7. Site 1 measures the flow input downstream of the Waingaro River-Takaka River confluence, site 3 measures flow at the Reileys roadend upstream of the Anatoki River-Takaka River confluence, and site 2 measures flow approximately halfway between sites 1 and 3, downstream of the Kotinga Bridge. The distances between sites 1 and 2, and sites 2 and 3 are approximately 1 km and 1.5 km respectively (Figure 4.7). Tidal effects are likely to influence the Takaka River flow further downstream of the Anatoki River-Takaka River confluence, namely at site 3 (pers. comm Doyle 1997). Because of this no further sites could be selected.

Flows recorded at sites 1-t, 2-t, and 3-t are 7115 l/s, 6796 l/s, and 6865 l/s respectively. Flow is lost to the TTG Aquifer between sites 1-t and 2-t, and is relatively stable between sites 2-t and 3-t (Table 4.4). Gauging information at these three sites, along with river levels (to mean sea level) is incorporated in the discussion of TTG Aquifer flow in section 4.3.4.

The estimation of recharge contribution from the Motupipi River comes from the analysis of a 1997 gauging run, involving four sites (1-m to 4-m) located between the Tasman Milk Products Dairy Company and Reileys Crossing (Figure 4.7). Results given in Table 4.4 show a 30 % loss in flow between sites 1-m and 2-m (this is from a total flow loss of 77 l/s). Flow gains are observed between sites 2-m and 3-m, and sites 3-m and 4-m. The numerous limestone springs which discharge into the Motupipi River account for this.

Table 4.4. Recharge contribution from the Lower Takaka River and the Motupipi River, for selected surveys in 1997 and 1998. Date time format is yymmdd format. Units are l/s

Motupipi River	Flow (l/s) (970318)	Lower Takaka River	Flow (l/s) (980323)
Site 1-m	227	Site 1-t	7115
Site 2-m	156	Site 2-t	6796
Site 3-m	280	Site 3-t	6865
Site 4-m	307		

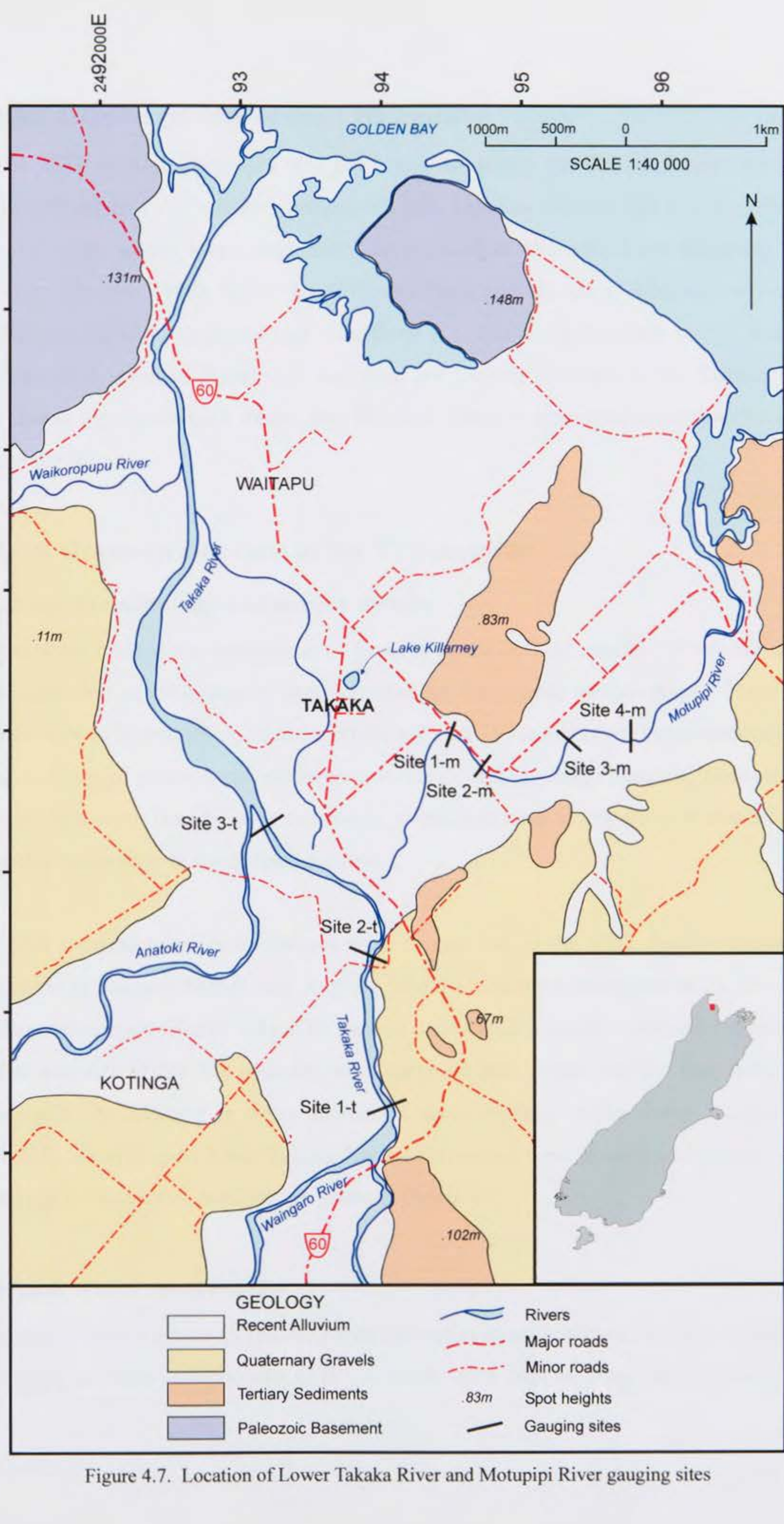


Figure 4.7. Location of Lower Takaka River and Motupipi River gauging sites

4.3.3 Discharge sites of the TTG Aquifer

The TTG Aquifer discharges into the lower reaches of the Takaka River (below the Anatoki River-Takaka River confluence), into Tekakau Stream, and into Golden Bay. Small scale gravel seeps have been documented at Waitapu, Lake Killarney (pers. comm. Thomas 1998), Roses Road, Paynes Ford, and Hamama. Seepage only occurs after periods of recharge and high river flows (i.e. they act as overflow seeps). Location of seeps is given in Figure 1.7, and most are located proximal to the Takaka River. Tekakau Springs (which drains into Tekakau Stream) represents a remergence of the Takaka River.

4.3.4 Groundwater flow in the TTG Aquifer

4.3.4.1 Terminology and survey details

The water table is the potentiometric level in an unconfined aquifer. Water elevations, as measured in wells, can be used to construct water-table surface maps. These are a basic tool of hydrogeological interpretation (Fetter 1994) and allow better understanding of direction of groundwater movement, recharge, and discharge patterns. Consideration of surface water features such as streams, rivers, and lakes is important in assessment of groundwater flow in unconfined aquifers.

Three separate water table surveys were carried out in the TTG Aquifer area in the months of January, March, and August. Water levels were monitored at 21, 24 and 25 sites respectively (Figure 4.8). The surveys used existing supply wells and fire hydrants. The majority of the fire hydrants were surveyed and leveled for the purposes of this analysis. In addition to water elevations, three sections of the lower Takaka River (below the Waingaro River-Takaka River confluence) were leveled and gauged for the March 1998 survey Localities are given in Figure 4.7.

4.3.4.2 Water level results

Reduced level water level (RLWL) with respect to mean sea level for each well and fire hydrant is listed in Appendix G-II. A water table contour map for the March 1998

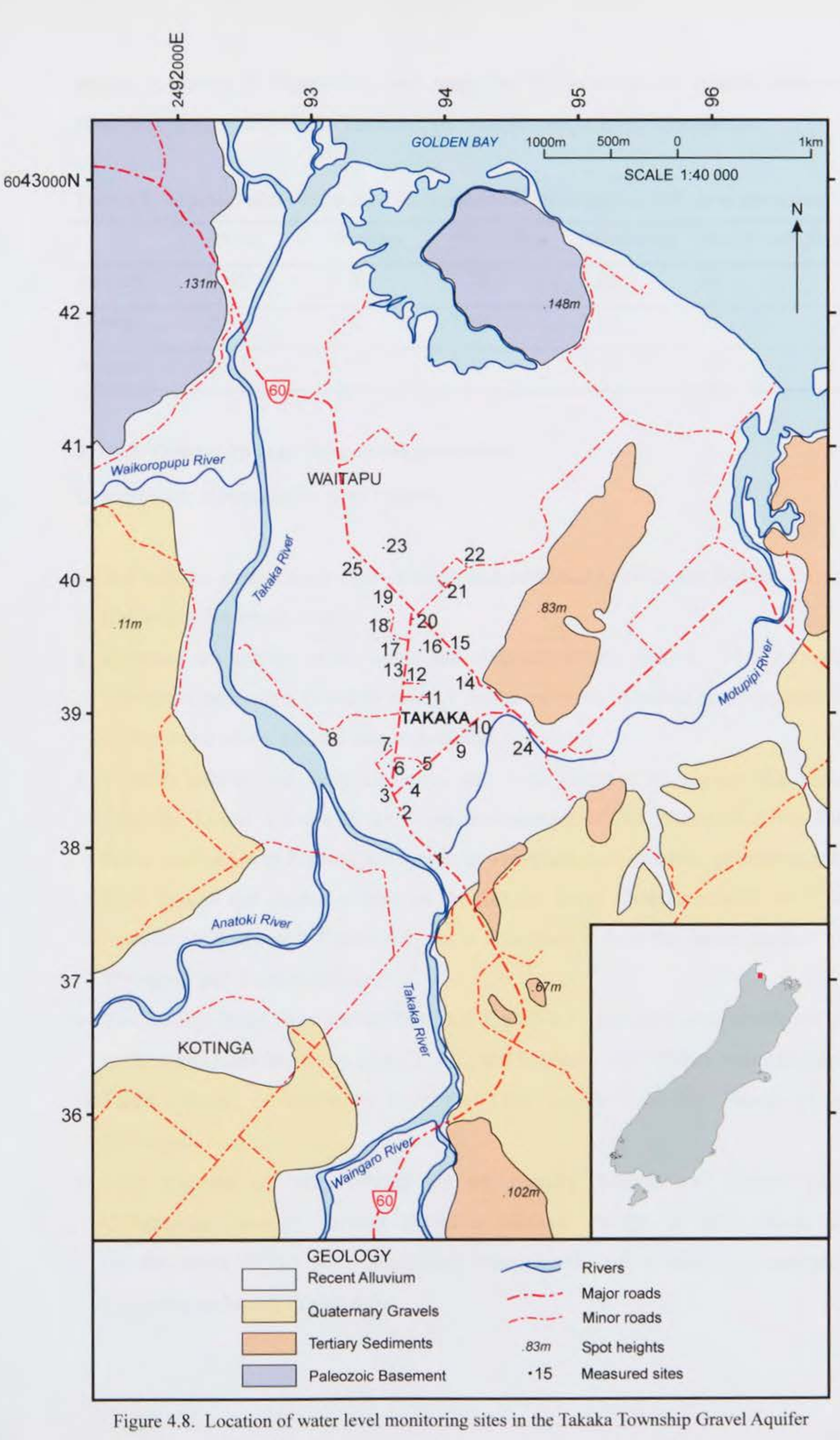


Figure 4.8. Location of water level monitoring sites in the Takaka Township Gravel Aquifer

survey is shown in Figure 4.9, and maps for the January and August surveys are presented in Appendix G-II. Table 4.5 summarises water level information.

Table 4.5. Summary statistics for the TTG Aquifer water level surveys 1997 (in m above msl).

	Mean	Median	Maximum	Minimum	No. of samples
January	5.65	5.56	7.79	3.66	24
March	5.87	5.82	7.93	3.90	25
August	6.17	5.97	8.36	4.53	20

4.3.4.3 Groundwater flow interpretation

Groundwater interpretation is as follows:

- The general groundwater flow is north and northeast towards the Golden Bay coast (the major discharge zone).
- Contours are convex to the north and relatively evenly spaced. The convexity is thought to indicate a possible zone of increased flow. Dashed contours have been extrapolated where limited data is available.
- Contour information, river elevation, and river gaugings all suggest that recharge from the Lower Takaka River (from downstream of the Waingaro River-Takaka River confluence to Kotinga Bridge) is an important contributor to groundwater flow. Flow loss in the shaded section of the Takaka River (downstream of the Kotinga recorder) is suspected (Figure 4.8), as is contribution from the lower reaches of the Waingaro and Anatoki Rivers.
- The Reileys Road river section (site 3-t, Figure 4.7) records a comparable elevation to the water table in nearby sites (3, 4, 5, and 6, Figure 4.8). Either recharge from the Takaka River, or discharge from the TTG Aquifer into the Takaka River is envisaged.
- Flow patterns are very similar for the January, March, and August surveys. Comparison between surveys shows a minimal change in mean water levels (of the order of 0.5 m). Maximum water levels are recorded in August, and minmums in March (Table 4.5).

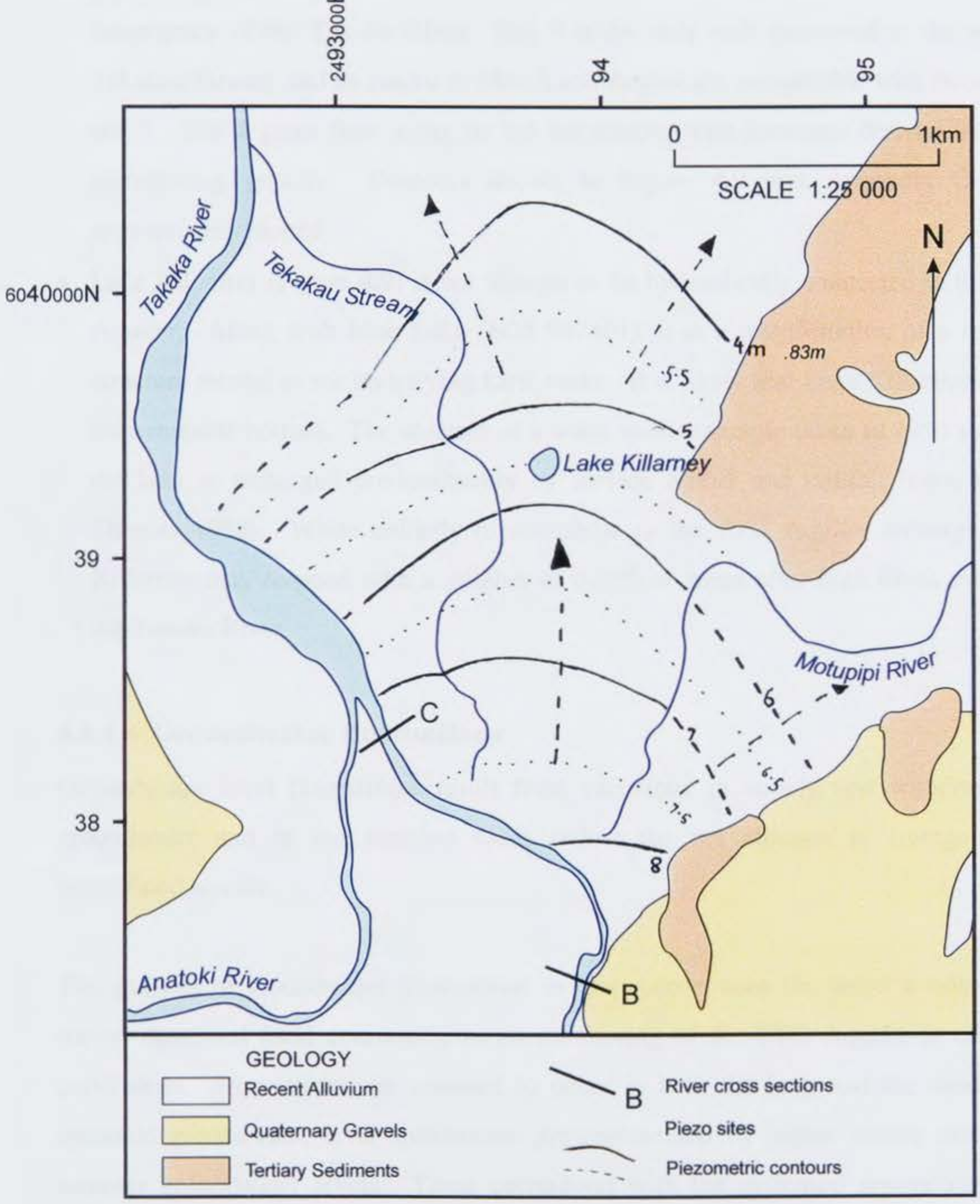


Figure 4.9. Water level contour map for TTG Aquifer, March 1998 survey

- The average hydraulic gradients for January and March, and August are 1.75 m/km, and 1.9 m/km respectively.
- Tekakau Stream, whose discharge depends on the head in the Takaka River, is a remergence of the Takaka River. Site 8 is the only well measured to the west of Tekakau Stream, and its results in March and August are comparable with those from site 7. Site 8 gains flow along its 2.5 km course, with increases derived from the surrounding gravels. Contours shown in Figure 4.9 and Appendix G-II are appropriately plotted.
- Lake Killarney (Figure 4.9) is not thought to be hydraulically connected to the TTG Aquifer. Along with Blue Lake (N25 947401), it is a manifestation of a collapse structure related to the underlying karst rocks. It is likely that Lake Killarney has an impermeable bottom. The analysis of a water quality sample taken in 1996 suggests the lake is recharged predominantly by surface runoff and rainfall (pers. comm. Thomas 1998). While unlikely to contribute to the TTG Aquifer recharge, Lake Killarney may respond with a number of overflow seeps after high flows events in the Takaka River

4.3.4.4 Groundwater fluctuations

Groundwater level fluctuations result from variations in supply and withdrawal of groundwater and in the simplest cases reflect the net changes in storage of an unconfined aquifer.

The analysis of groundwater fluctuations in this chapter uses the writer's water level survey data, and local comments, as no monitoring of the TTG Aquifer is currently undertaken. Fluctuations are assumed to occur in both the long and the short term. Seasonal groundwater level fluctuations are represented by higher winter and lower summer groundwater levels. These correspond with the increased precipitation and river levels during the months of August to October, and the corresponding lows between January and March. The extent of seasonal groundwater level variation is unknown, as is the overall groundwater trend. Because of the unconfined nature of the aquifer, it is expected that TTG will display an immediate and pronounced short term response to rainfall and river recharge events. Negligible pressure effects have to be assumed. Localised decreases in groundwater level are expected during periods of increased usage. Short term responses will be the result of pressure response as opposed to actual throughflow of water; isotope analysis by Stewart and Williams (1981) suggests a typical throughflow time of 3 to 4 months.

4.4 THE EAST TAKAKA GRAVEL AQUIFER

4.4.1 Aquifer description

The East Takaka Gravel aquifer represents a localised region of the extensive Quaternary gravel deposits of the Takaka Valley. The aquifer extent for this thesis is bounded to the east by the Pikikiruna Range and to the west by the Takaka River. It has a total area of 10.1 km^2, and is comprised of two separate sections, namely 5.6 km^2 of gently contoured river gravels, and 4.5 km^2 of Bainham I and II terraces. Description and characteristics of Bainham deposits are presented in Table 2.1. The southern and northern boundaries of the TTG Aquifer are Gorge Creek and Rameka Road respectively (Figure 2.12). The underlying confining material is Tarakohe Mudstone, which crops out at the base of the Pikikiruna Scarp on the eastern aquifer boundary (Section 2.6.2).

Domestic and agricultural water supply is serviced by the conjunctive use of surface and groundwater from the East Takaka region. The ETG Aquifer is used, along with the ETML Aquifer and surface water derived from the gravity fed Gorge Creek scheme. There are 21 shallow gravel wells listed in the Tasman District Council Well Archives. Demand for groundwater, especially from the farming sector, is likely to increase.

4.4.2 Recharge sources of the ETG Aquifer

The primary recharge sources of the ETG Aquifer are as follows:

1. diffuse input from rainfall infiltration over the total aquifer extent (i.e. over both the recent gravels and the terrace deposits),

2. Infiltration from intermittent streams which flow from the Pikikiruna Range and from the high terraces in the northeast of the aquifer area (after heavy rainfall events), and

3. Input from the Takaka River, appearing to affect the river gravel deposits rather than the Bainham terraces.

A gross estimate for diffuse rainfall contribution, based on an annual average rainfall of 2600 $mmyr^{-1}$, a total aquifer extent of 10.1 km^2, and an assumed infiltration percentage of the order of 50 %, is 0.4 m^3s^{-1}, or 130×10000 myr^{-1}.

Information regarding the Takaka River contribution to recharge comes from discussions with local landowners. The WWD 6827, located approximately 450 m from the Takaka River (at N26 945328), responds to increasing or decreasing river flows (pers. comm. Rodgers 1997). The influence of the Takaka River contribution to ETG Aquifer water levels is likely to be localised. However, water levels in WWD 6817, located approximately 1100 m from the Takaka River and situated in Bainham I terrace deposits, do not appear to be affected (pers comm. Rodgers 1997).

Estimation and/or quantification of recharge inputs is difficult.

4.4.3 Discharge sites of the ETG Aquifer

No prominent discharge zones for the ETG aquifer are identified. No seeps issuing from the gravels are observed or identified in the East Takaka region. The major discharge zone for ETG would be on the boundary between the Takaka River and theEast Takaka gravels, in the lower reaches immediately prior to Paynes Ford.

4.4.4 Groundwater flow in the ETG Aquifer

4.4.4.1 Terminology and survey details

Four water level surveys were conducted during 1997 in East Takaka, in order to establish any apparent seasonal trends, and to establish groundwater flow patterns for the ETG Aquifer. The surveys were carried out on 20 March, 12 June, 16 September, and 18 December, and incorporated 14 shallow wells (Figure 4.10) which were only open to the ETG Aquifer. The surveys covered a 3 hour period. All wells used in the survey had been previously surveyed to mean sea level. The majority of these wells were not being used for domestic purposes, providing only irrigation and stock water. During the survey periods there were only five occasions that wells were in use. In these instances it was ensured that pumped wells had been shut off long enough in order that the water level could recover to a static or non pumping level.

4.4.4.2 Water level results

Reduced level water levels (RLWL) with respect to mean sea level for all wells surveyed are presented in Appendix G-III. The well depths range from 2.7m to 14m. The water level contour map for the ETG Aquifer for 20 March is shown in Figure 4.11, with information for other surveys presented in Appendix G-III. Measurable wells are confined to a fairly limited west to east spread, consequently contours have only been drawn where data points allow. Summary statistics are presented in Table 4.6.

Table 4.6. Summary data for the ETG Aquifer water level surveys 1997, in m above msl.

	Mean	Median	Maximum	Minimum	No. sample
March	26.43	26.32	29.81	21.98	14
June	26.75	26.98	29.76	21.94	14
September	28.25	28.87	32.64	23.11	13
December	26.92	27.61	30.10	21.99	13

4.4.4.3 Interpretation of groundwater flow

Specific features from Figure 4.11, Table 4.6 and Appendix G-III are as follows:

- The general groundwater flow is north to northwest (this is in concordance with discharge to the north to northwest).
- The contours in the March survey (Figure 4.11) are variably spaced and shaped. At the south end they are close and relatively flat, while in the north they are more widely spaced towards the Takaka River and more closely spaced at the foothills.
- The contour pattern shows that the north-eastern area receives recharge from the higher terraces.
- Variable hydraulic gradients have been estimated, ranging from 2 m/km in the south to 3 m/km in the north section.

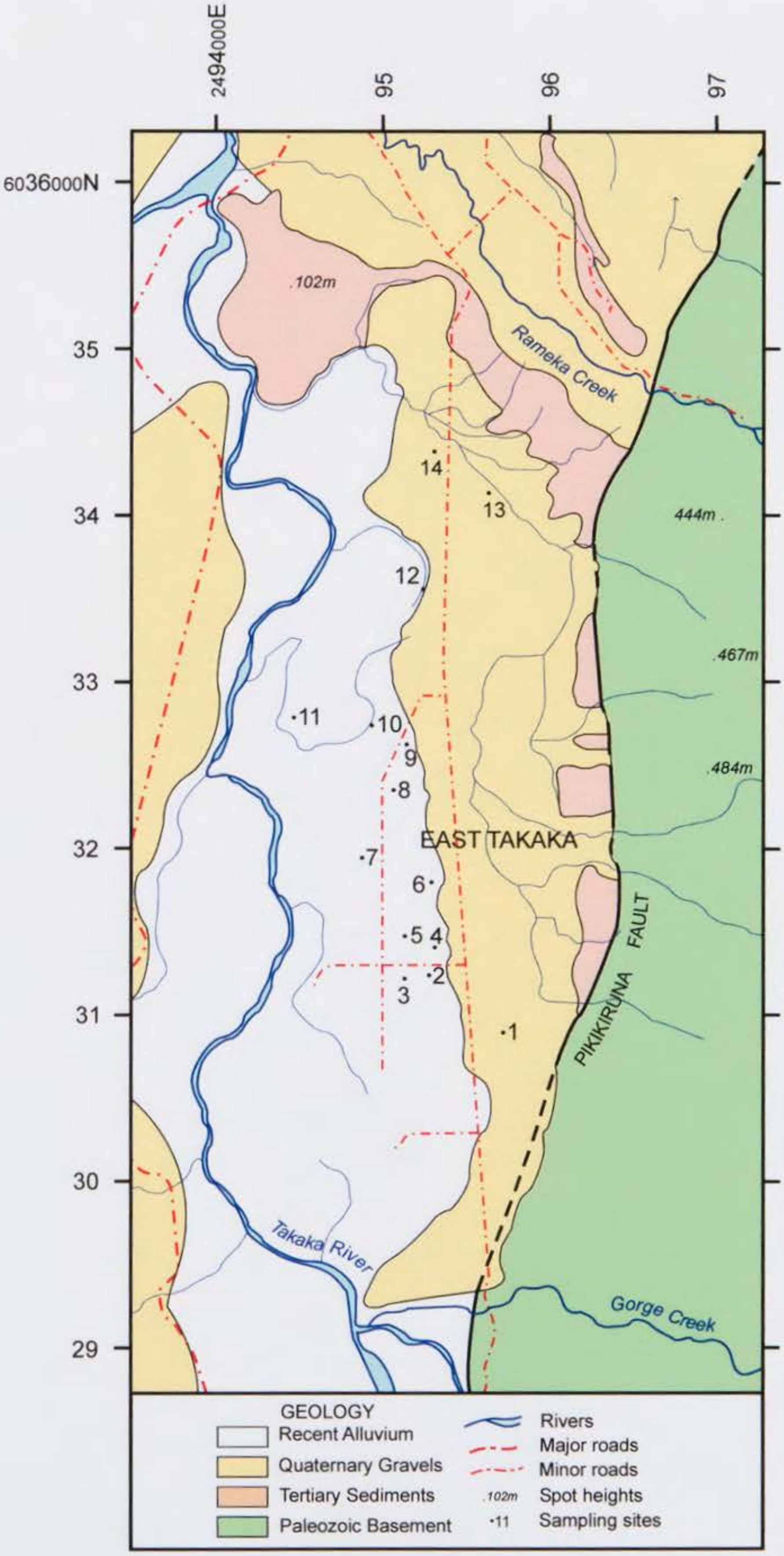


Figure 4.10. Location of water level monitoring sites in the East Takaka Gravel Aquifer

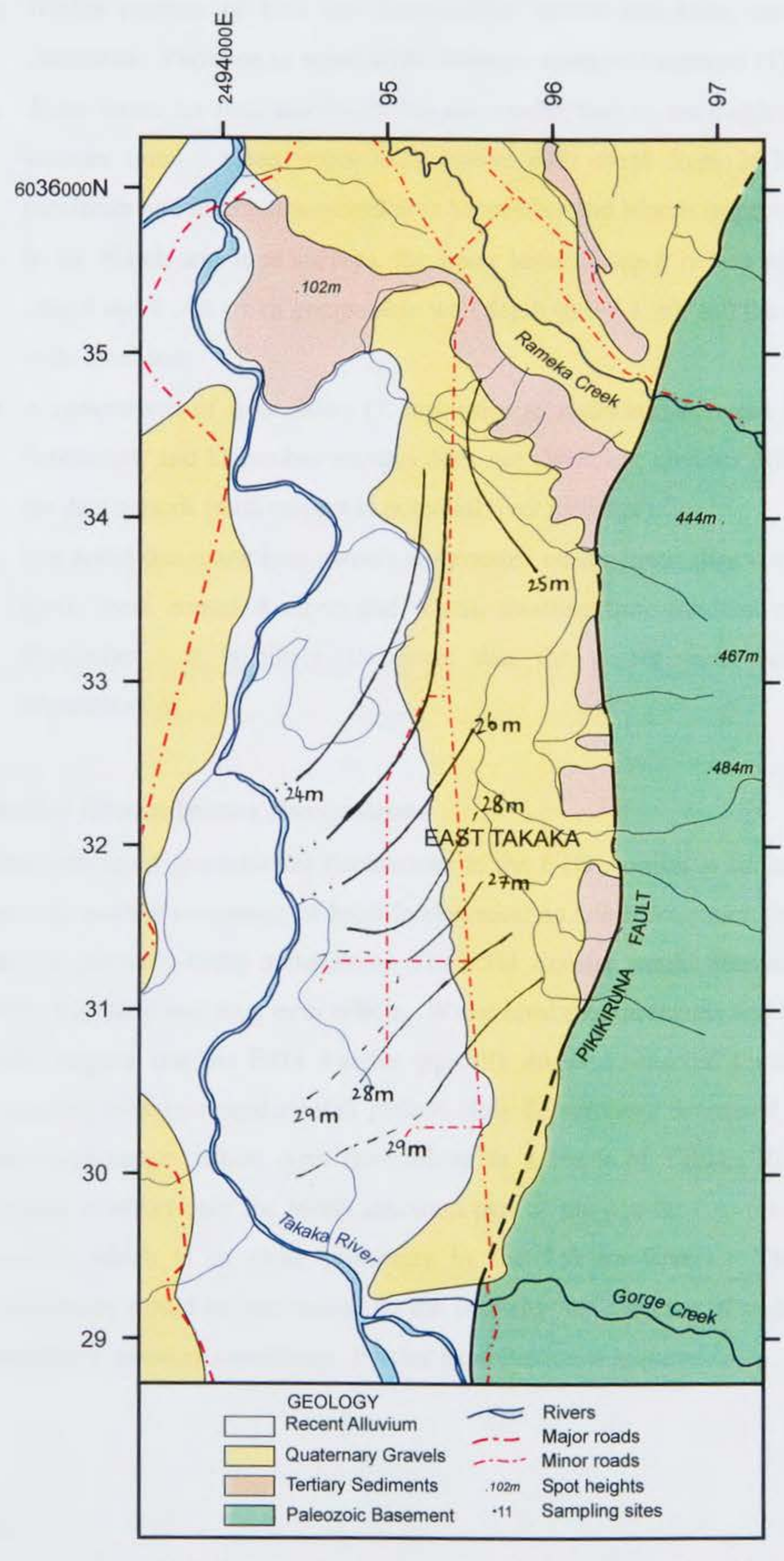


Figure 4.11. Water level contour survey for ETG Aquifer, March 1997 survey

- Similar patterns of flow are observed for March and June, and September and December. Variation in water levels between surveys is minimal (Table 4.6).
- Water levels for June and December are similar, and do not display a strong winter-summer trend. Mean water level (above msl) range from 26.36-28.17 m, with maximum and minimums recorded in September and March respectively (Table 4.6).
- In the March and June surveys, the water level of site 5 is 1 m higher than nearby sites 3 and 4. All are of comparable well depth (6.9-7.1 m), and the effect is assumed to be localised.
- A comparison of river flows (7 days prior to sampling) between the March, June, September, and December surveys does not show any obvious differences between the data periods (with respect to potential river recharge).
- It is noted that many land owners commented on the lower than normal winter water levels (pers. comm. Rodgers and Ward), resulting from minimal rainfall in May to September. It is likely, therefore, that the winter water level map is not representative.

4.4.4.4 Groundwater fluctuations

The analysis of groundwater fluctuations in the ETG Aquifer is limited to water level surveys and the comments of local landowners; no continuous monitoring of any ETG sites is presently being undertaken. The ETG Aquifer would fluctuate in response to both short term and long term effects. Water level measurements and local comment in 1997 suggest that the ETG Aquifer typically displays seasonal fluctuations. This is correlated with increased rainfall periods (July-September), decreased evaporation, and decreased usage. Short term fluctuations as a result of Takaka River recharge are thought to effect only the recent alluvium part of the aquifer (i.e. the part of the ETG Aquifer which is in close proximity to the Takaka River). The magnitude of fluctuations would be determined by the intensity and duration of recharge events, and antecedent moisture conditions. Further examination is required.

4.5 FURTHER WORK AND MONITORING REQUIREMENTS

4.5.1 The ETML Aquifer

An in-depth geological and hydrogeological study of the ETML Aquifer area is required. This will allow a more detailed subdivision of the ETML Aquifer into sub-aquifers. Delineation of these sub-aquifers and confirmation of their semi-isolated or isolated nature is required, in order that the groundwater resource of the ETML Aquifer be effectively managed.

Specific geological studies are needed. These include an accurate mapping of the western boundaries of both the East Takaka sub-aquifer and the Central Takaka-Motupipi sub-aquifer, together with structural mapping involving fracture trace analysis and fold delineation. Any future drillholes must be logged in detail.

The specific monitoring of principal spring discharges is needed to ascertain output of the sub-aquifers or the entire ETML Aquifer. The continuous measurement of a representative Central Takaka bore (i.e. one in the north-western fold belt shown in Figure 2.6) is needed to assess the potential subdivisions within the Central Takaka-Motupipi sub-aquifer. Water resource management directives include a further investigation of the existence of submarine springs related to the karstic limestone, and the development of an aquifer water balance, or more appropriately, of sub-aquifer water balances.

4.5.2 The TTG Aquifer

A continuous monitoring site needs to be installed in the TTG Aquifer in order to enable assessment of aquifer fluctuations (long term trends and seasonal fluctuations), and of response to recharge (short term trends). A monitoring well located central to the Takaka Township would provide the most representative information. A specific monitoring well would also be suitable for pump test analysis, allowing assessment of aquifer characteristics. A more detailed tri-study (incorporating water level measurements, river levels, and river gaugings) should be undertaken. The tri-study in this thesis used 3 river sites downstream of the Waingaro River-Takaka River confluence. An additional 3-5 sites (incorporating sites downstream of the Anatoki

River-Takaka River confluence) should be incorporated. Tidal conditions will need to be considered prior to undertaking the survey. Water level surveys should be conducted on a regular basis, in order to build up a spatial data base.

4.5.3 The ETG Aquifer

Further delineation between the Bainham terrace section and the river alluvium section of ETG is required. Distinctions need to be drawn as to whether these sections response differently to recharge events, have different flow paths, or contain variable water reserves. In terms of assessing the recharge contribution from the Takaka River it is suggested that a survey incorporating between 4-8 river gaugings, 4-8 river levels, and using comprehensive water level monitoring be implemented. More measurable wells need to be incorporated in the water level surveys, in order to increase the west to east spread of the existing sites At present, some usefully situated wells are not accessible. Continuous monitoring of at least one selected well in the ETG Aquifer would enable the evaluation of water table fluctuations.

4.6 SYNTHESIS

The study of the limestone and gravel aquifers of East Takaka and Takaka Township raises important water resource management issues.

- The East Takaka-Motupipi Limestone Aquifer is the minor karst aquifer in the Takaka Valley.
- ETML can be subdivided into three sub-aquifers. The two which lie in the Takaka Catchment are named the East Takaka and the Central Takaka-Motupipi sub-aquifers. Further geological assessment of the sub-aquifer system is required.
- Principal recharge sources for ETML are the Takaka River, diffuse rainfall, and input via stream sinks.
- Particular components of recharge affect particular sub-aquifers There are strong structural and geomorphological controls on recharge processes.
- Groundwater fluctuations are seasonal, lower in summer and higher in winter. Short term fluctuations are in response to recharge. Tidal fluctuations are noticed close to the coast.

- The Takaka Township Gravel Aquifer and the East Takaka Gravel Aquifer are important sources of water for domestic and agricultural use in the area.
- The Takaka Township Gravel Aquifer is primarily recharged from diffuse rainfall and water from the lower reaches of the Takaka River. The Motupipi section of TTG gets recharge from the Motupipi River.
- A number of discharge sites of TTG have been identified close to the Takaka River. Other sites act as overflow seeps when groundwater levels are high.
- General groundwater flow is in a north to northeast direction. Levels are assumed to fluctuate in response to seasonal and short term events.
- The East Takaka Gravel Aquifer has two distinct sections, namely the Bainham terrace section and the river alluvium section. Principal recharge sites are diffuse rainfall and input from the mid Takaka River, which appears to have more effect on the river gravel.
- General groundwater flow is in a north to northwest direction. Fluctuations are assumed to be the result of seasonal and short term events.
- More monitoring of all three aquifers is required for better quantitative analysis.

CHAPTER FIVE : WATER CHEMISTRY AND QUALITY OF THE TAKAKA VALLEY AQUIFER SYSTEM

5.1 INTRODUCTION

A study of water chemistry and water quality is an integral part of a hydrogeological investigation. Water quality analysis must incorporate information on surface water, groundwater recharge, flow dynamics, and landuse effects. Accurate assessment (both spatial and temporal) can determine any changes or trends, and can identify areas where the water quality has been degraded. Often the existing water quality databases are inadequate.

In this chapter, baseline water chemistry and quality assessment are provided for the three main aquifers in the Takaka Valley, as a foundation for future studies.

The objectives of this chapter are:

- to describe the chemistry (major ions, and physical properties) of the three main aquifers,
- to assess any regional variations and aquifer-specific chemical fingerprints, and
- to describe water quality (microbiological, and chemical determinands of health and aesthetic significance) of the three main aquifers, ascribing their potential use for particular purposes.

Analysis uses the existing database available for the Takaka Valley aquifers and surface waters, and involves the following surveys:

- surface water data for the Takaka River and major and minor tributaries (1988-1998),
- TTG Aquifer and ETG Aquifer 1996 comprehensive survey,
- TTG Aquifer and ETG Aquifer nitrate results (1986), and
- Pupu Springs and WWD-6601 (ETML Aquifer) analysis (1990-1997).

Data analysis in this chapter is limited to one survey in the gravel aquifers, and to an extensive temporal database for single sites in the WAM and the ETML Aquifers. It must be understood that a single analysis (as in the TTG and ETG survey) can be insufficient for proper assessment of conditions (Hounslow 1995). The analyses given in this chapter are intended to provide baseline assessments of water quality variables, on which further studies can build.

5.2 WATER QUALITY INITIATIVES

5.2.1 Past investigations

Past surveys in surface and groundwater resources in the Takaka Valley have been erratic. Aside from one-off groundwater samples (for individual well owners, etc.) comprehensive surveys of the gravel aquifers have been confined to two surveys in 1986 and 1996. The former survey was conducted primarily to assess nitrate concentrations, and did not involve analysis of other ions. The 1996 survey was comprehensive, and involved 24 sites (over the TTG and ETG Aquifers), of which eight underwent major analysis. Limited miscellaneous spring samples were taken (at East Takaka Springs, Spring Brook, and Motupipi Springs) and analysed. More in-depth studies of Pupu Springs were undertaken. Water chemistry of Pupu Springs was investigated by Michaelis (1974, 1976), and regular sampling by the Tasman District Council (TDC) is ongoing.

Major surface water assessments of the Takaka River and its major and minor tributaries were conducted in 1987 (Bruce 1987), and in 1989 and 1992 (Roberts 1993). Bruce (1987) and Roberts (1993) established baseline information on instream values, invertebrate assemblages, nutrients, and water quality variables. Discussions in this chapter will not cover the biological ramifications of water chemistry and quality, and the reader is referred to Roberts (1993) and Bruce (1987).

Analyses of all surface water and gravel aquifer water samples were performed at the Cawthron Institute, Nelson.

5.2.2 Current water chemistry and quality investigations

An existing three-monthly sampling programme of the two karst aquifers in the Takaka Valley is presently undertaken by TDC. Sample localities are Main Springs (representing groundwater outflow of WAM), and WWD 6601 (a borehole located in Central Takaka, representing groundwater of ETML). In the following sections, the WAM sampling site (Main Springs) will be referred to as Pupu Springs.

Implemented in 1990, Pupu Springs monitoring is part of the wider national groundwater management programme (NGMP) conducted by regional/district councils and by the Institute of Geological and Nuclear Sciences (IGNS). The aim of the sampling is to build up extensive temporal databases which will allow accurate assessment of trends and changes in water chemistry. Analyses for Pupu Springs and WWD-6601 are conducted by IGNS, Wairakei. Ongoing sampling of the gravel aquifers in the Takaka Valley does not exist at the present time.

5.3 SURFACE WATER CHEMISTRY AND QUALITY

5.3.1 Influences of surface water chemistry and quality

Surface water chemistry and quality in the Takaka Valley (including the Takaka, Waingaro, and Anatoki Rivers, and their minor tributaries) are affected by several factors. These are as follows:

- The geology of the Takaka Valley contains both karstic and alluvial components. Takaka Catchment geology is varied, as shown in Chapter One.
- Landuse in the Takaka Valley is predominantly agricultural, mainly dairying, with some grazing and limited cropping and forestry. Landuse intensity increases down the valley. Agricultural activities are assumed to be the primary sources of diffuse and point source contamination.
- The hydrological regime, in particular, the antecedent flow conditions, also has an important influence. The upper Takaka River is affected by irregular flow releases from the Cobb power station.

5.3.2 Importance of assessing surface water quality

There are four major reasons for assessing surface water quality:

- Surface water can influence groundwater quality when water level gradients cause the infiltration of water (Matthess 1982). Takaka River water is a major recharge contributor to the gravel and karst aquifers in the Takaka Valley. The Upper Takaka River (between Lindsays Bridge and upstream of Stoney Creek) contributes 55 % of recharge to the WAM Aquifer (Section 3.2), while the lower and middle sections of Takaka River (Kotinga-Reileys Road) contribute to the TTG Aquifer (Section 4.3). It is therefore vital to recognise and assess surface water quality prior to a study of groundwater quality.
- Surface water quality can have a profound affect on instream values, and biological values.
- The appearance of water (i.e. the clarity, turbidity, and colour) is determined by water chemistry and quality, and can have ramifications for recreational uses.
- Water quality, and the presence of microbiological determinands, has profound effects on the suitability of surface water for drinking water purposes.

5.3.3 Assessment of water chemistry and quality

Because factors such as flow conditions, antecedent flow, rainfall, and seasonality result in ion and physical parameter variation, surface water information for the Takaka Valley is collated and summarised to provide an overall data set (in the form of means, maximums, and minimums). Comparative survey assessment is not of primary interest. Table 5.1 is a summary of water chemistry/quality data collected for the Takaka River (separated into upper, middle, and lower sections), Anatoki River, and Waingaro River, from 1987 to 1997 (Figure 5.1). Full details of all available data are presented in Appendix H-I. The number of surveys incorporated in calculations is noted, and varies between river sections and rivers. The most recent surface water assessment, conducted in 1992 (Roberts 1993), provided chemical as well as useful microbiological information.

SUMMARY STATISTICS FOR SURFACE WATER QUALITY ASSESSMENT IN THE TAKAKA RIVER AND MAJOR TRIBUTARIES																				
	TAKAKA RIVER												WAINGARO RIVER				ANATOKI RIVER			
VARIABLE -	UPPER TAKAKA RIVER (Harwoods - Craigieburn)				MID TAKAKA RIVER (Paynes Fd - Kotinga)				LOWER TAKAKA RIVER (Roses - Waitapu)				Hanging Rock - Confluence				Happy sams - Confluence			
gm^3 unless stated	Mean	Maximum	Minimum	no samples	Mean	Maximum	Minimum	no samples	Mean	Maximum	Minimum	no samples	Mean	Maximum	Minimum	no samples	Mean	Maximum	Minimum	no samples
pH	7.6	8	7.3	10	7.6	8	7.3	4	7.6	7.8	7.3	2	7.5	8.3	7.2	6	8.1	8.9	7.8	4
Conductivity (mS/m)	7.9	8.9	7.1	7	8.6	9.6	7.8	4	6.5	7.2	5.8	2	8.6	8.8	8.4	3	9.3	11.1	7.5	2
Calcium	12.9	15.7	10.1	7	15.5	17.4	12.7	3	13.7	nc	nc	1	15	16.2	11.9	5	23	27	20.6	3
Magnesium	2.6	2.8	2.4	7	1.9	2.15	1.6	3	1.8	nc	nc	1	2.1	2.3	1.8	5	1.7	1.8	1.7	3
Sodium	2.2	2	2.4	7	2.3	2.4	2.1	3	2.3	nc	nc	1	3.1	3.7	2.4	5	2.2	2.4	2	3
Potassium	0.25	0.3	0.17	7	0.4	0.5	0.3	3	0.4	nc	nc	1	0.4	0.58	0.28	5	0.31	0.33	0.26	3
Bicarbonate	48.5	54	46	4	42	nc	nc	1				nm	52	59	42	4	66	67	65	2
Chloride	2.3	3	1.8	7	2.5	2.9	2.3	3	1.2	nc	nc	1	2.9	3.6	2.3	5	1.7	2	1.5	3
Sulphate	2.8	3.7	1.2	7	2.2	2.6	1.8	3	<1.0	nc	nc	1	3.1	4.1	1.9	5	2.8	3.4	1.9	3
Nitrate	12	35	0.012	6	58.6	150	0.08	4	79.9	140	0.029	3	13	26	0.032	2	16	32	0.032	1
Ammonia	30	<0.001	85	6	6.5	21	<0.001	4	22.7	56	<0.001	3	2.5	<5	0.009	5	<2.5	<5	<0.09	1
Alkanility	37	44	33	7	37	39	34	3	41	nc	nc	1	42	48	35	5	54	55	53	3
Free CO2	2.2	2.3	2.1	3	7.6	8	7.3	4	3.5	nc	nc	1	2.3	nc	nc	1	2.2	nc	nc	1

nm = not measured, nc = not calculated

Table 5.1. Summary details of water quality data collected for the Takaka River (divided into upper, middle, and lower sections) and major tributaries. Full details are presented in Appendix H-I

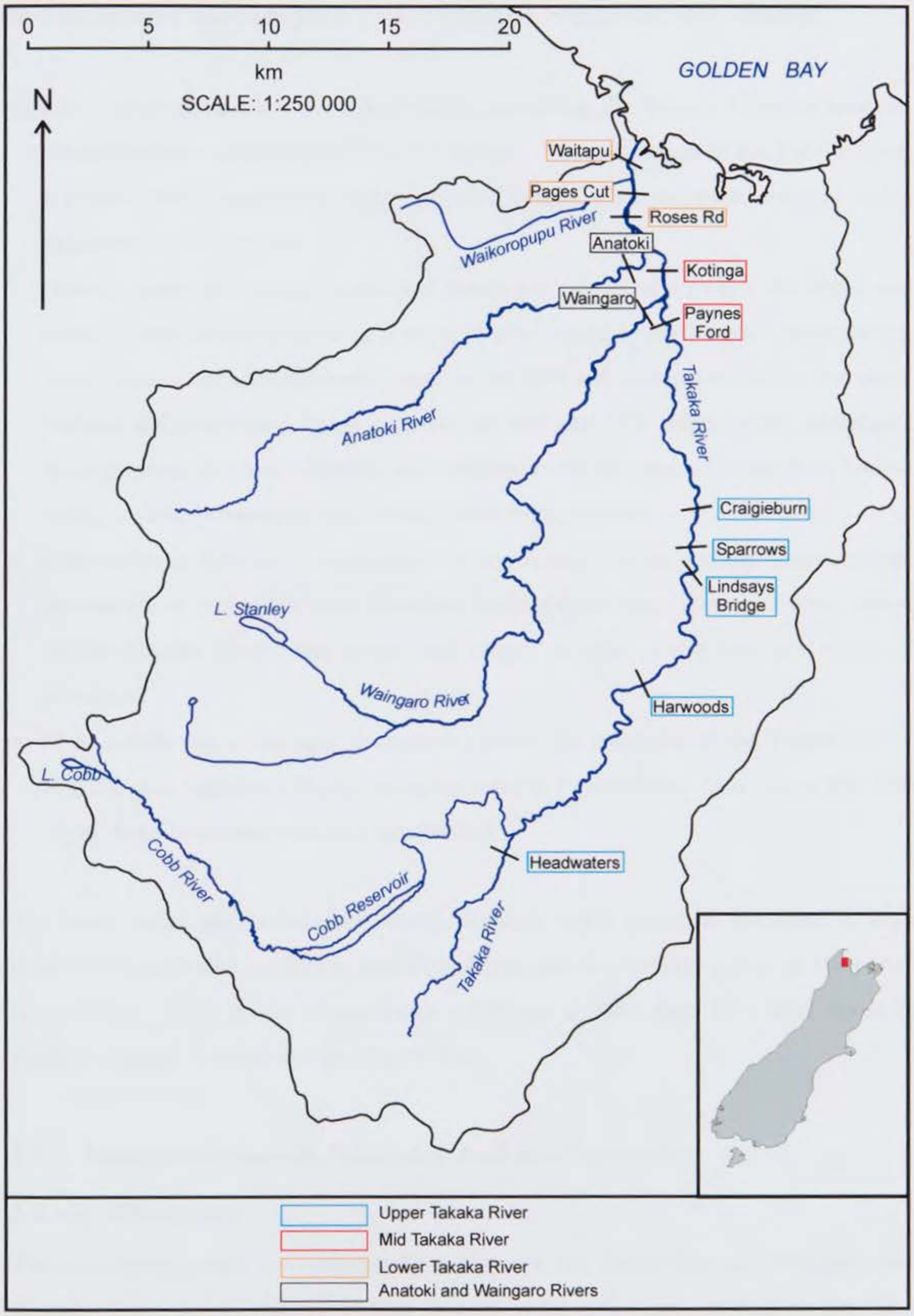


Figure 5.1. Location of surface water quality sampling sites in the Takaka Catchment

Specific features (shown in Table 5.1 and Appendix H-I) include the following:

- Little recorded variance in conductivity occurs along the Takaka River, or between tributaries (the overall range is 6.5-11.1 mS/m). The midsection of the Takaka River at Paynes Ford typically has higher recorded values, when compared with the upper and lower river stretches.
- Overall, mean sodium and potassium levels are consistent between the upper and middle Takaka River sections (2.2 and 0.25 g/m^3, and 2.3 and 0.4 g/m^3 respectively), mean calcium and chloride levels increase (by 20% and 10% respectively), and mean sulphate and magnesium levels decrease (by 20% and 25% respectively). Decreases in magnesium, sulphate, chloride, and calcium levels are observed (based on limited survey results) between the middle and lower river sections.
- Both the mean calcium concentrations in the Anatoki River and the mean chloride concentrations in the Waingaro River are slightly higher than their equivalent values for the Takaka River. The means and ranges of other major ions are relatively consistent.
- Mean nitrate values increase dramatically down the mainstem of the Takaka River, with the peak value of 150 g/m^3 being recorded at Paynes Ford. Low values less than 1 g/m^3 have been recorded at the headwaters.

The most recent microbiological survey (Roberts 1993) recorded moderate to high numbers of confirmed coliforms, faecal coliforms, and *Escherichia coli* at all river sites (Figure 5.2). High levels of confirmed coliforms (greater than 350) were noted at Paynes Ford and Waitapu Bridge (Figure 5.2).

5.3.4 Interpretation of chemistry and quality data

5.3.4.1 Chemistry

The variation in major ion concentrations between the Upper Takaka, Waingaro, and Anatoki Rivers can be related (at least in part) to the differences in local geology and surficial deposits. The mid to lower Takaka river water is comprised of inputs from the Upper Takaka, Waingaro, and Anatoki Rivers, and its chemistry thus reflects this mix. Overall, as a major source of ground water recharge to the WAM Aquifer, the Upper

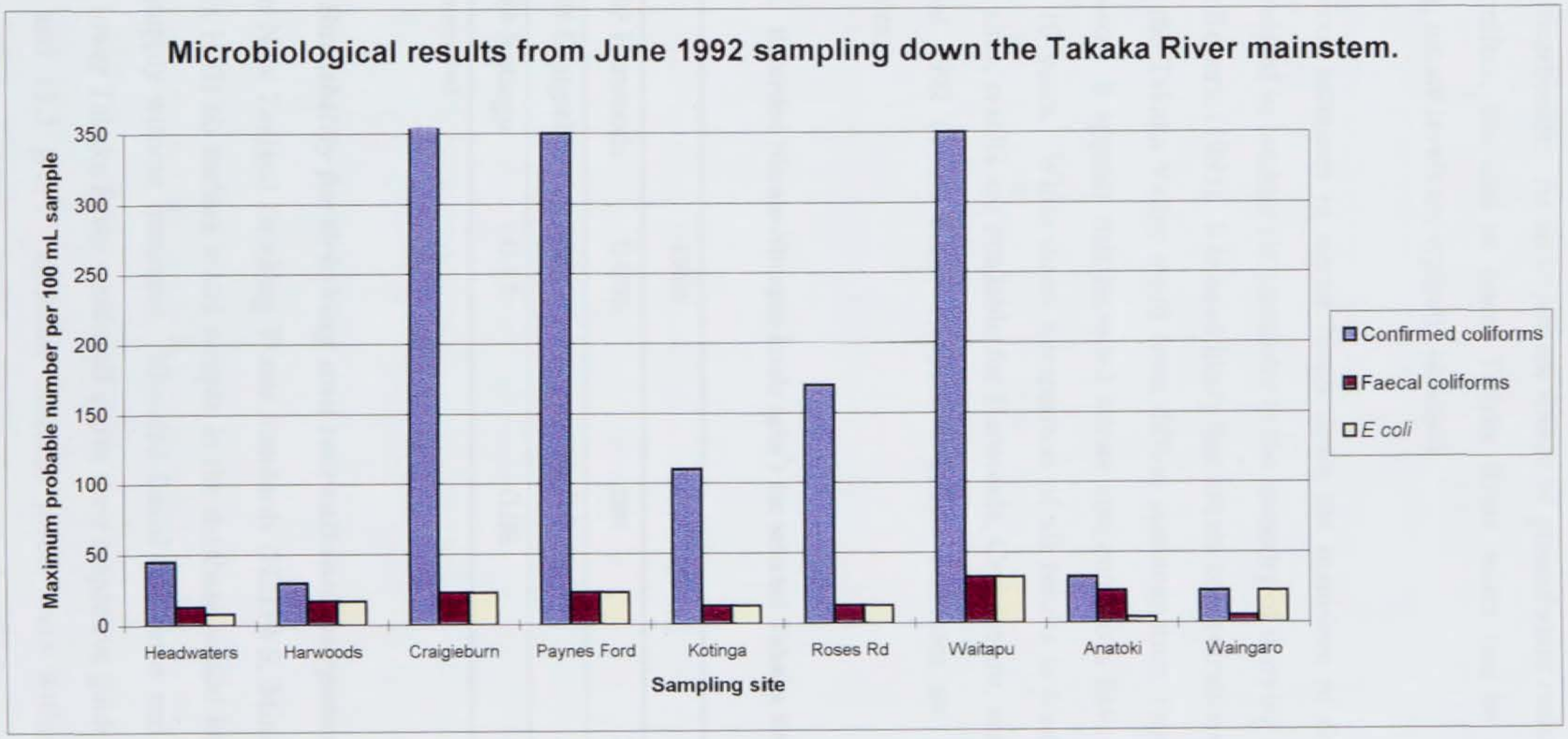


Figure 5.2. Comparison of microbiological results for the Takaka River and tributaries (June 1992 sampling)

Takaka river water can be described as being of low electrical conductivity, with low concentrations of all ionic species; the dominant cation is calcium, and the dominant anion is bicarbonate. As an important source of groundwater recharge to the TTG and ETG Aquifers, the mid to lower Takaka River water can be described similarly. However, nitrate levels are typically elevated.

The obvious increases in nitrate levels down the mainstem of the Takaka River are directly related to landuse (in particular to the intensity of dairying and pastoral use), as noted by Roberts (1993). It is most likely that nitrate concentrations entering the surface water in the Takaka Valley result from diffuse contamination, rather than any specific point source. It appears that recorded nitrate concentrations have increased greatly in the past 10 years. While direct comparison of all results is hindered by the lack of multiple sites, results are available for Harwoods, Craigieburn, and Kotinga, for 1986, 1987, and 1992 (Table 5.2). Respective nitrate increases are in the order of 2-3 magnitudes.

Table 5.2. Recorded Nitrate-Nitrogen levels (g/m^3) for selected Takaka River sites in 1986, 1987, 1992.

Site	1986	1987	1992
Takaka @ Harwoods	0.006	nm	27
Takaka @ Craigieburn	nm	0.012	35
Takaka @ Kotinga	0.13	0.08	84

nm = not measured

5.3.4.2 Suitability for drinking and recreational purposes

Based on New Zealand Drinking Water Standards (NZDWS, Ministry of Health 1995, Appendix H-II) no surface water sample in the database would have been suitable for potable supply without treatment. Elevated faecal coliforms and nitrate levels in the mid and lower Takaka River were well above their respective guideline values of nil per 100 ml and 11.3 g/m^3. Indicator bacterial levels were within contact recreation guidelines (Roberts 1993). These results are assumed valid for surface water quality at the present time.

5.4 GROUNDWATER CHEMISTRY AND QUALITY

5.4.1 Influences on groundwater chemistry and quality

The chemistry and quality of groundwater is determined by a large number of variables, which include the presence of dissolved chemical constituents, physical characteristics, and anthropogenic influences. Groundwater chemistry will not simply be a reflection of major recharge sources (i.e. river and rainfall). As groundwater moves from recharge to discharge zones, its chemistry is altered by the effects of a variety of geochemical processes (Freeze and Cherry 1979). Potentially important factors which impact on the water chemistry of the gravel and karst aquifers of the Takaka Valley are:

- chemical reactions, including dissolution processes, oxidation-reduction reactions, ion exchange process, reactions resulting from decomposition of source rocks,
- physical controls, including restricted flow paths, aquifer extent, recharge sources, and discharge sites, and
- human influences, including introduction of contaminants, and influence of industrial activities.

5.4.2 Importance in assessing groundwater chemistry and quality

There are three reasons for assessing groundwater chemistry and quality. Firstly, chemical analyses can provide useful information regarding the source of groundwater, inter-aquifer reactions, and source rock deduction. Secondly, chemical data analysis allows spatial and/or temporal trends to be assessed, so that areas of deteriorated or deteriorating water quality can be identified. Lastly, the chemistry and quality of groundwater determines its suitability for agricultural and domestic supply.

The gravel aquifers and the minor karst aquifer in the Takaka Valley provide water for domestic, agricultural, and minor industrial supply and must therefore be suitable for irrigation purposes, livestock, and drinking. WAM has its primary discharge at Waikoropupu Springs. Both features inherently require the protection and preservation of their water quality.

5.4.3 Gravel aquifers - the TTG and ETG Aquifers

5.4.3.1 Spatial analysis of groundwater chemistry and quality

Analysis of discrete surveys over the spatial extent of an aquifer enables specific areas of water quality degradation to be identified. Assessment of the water quality of the TTG and ETG Aquifers uses one comprehensive survey in 1996 (incorporating 19 samples) and is supplemented by nitrate data gathered in 1986 (incorporating 11 sites). Information has been presented as summary statistics, and as stiff plots and areal figures. These plots allow a simplified comparison of sites which are spatially dispersed. Stiff diagrams use up to four parallel horizontal axes extending on each side of a vertical zero axis (Hounslow 1995). The size of the pattern, drawn with either a log or linear meq/l scale (milliequivalents per litre), is approximately equal to the total ionic content. Classic cation and anion pairs are sodium-chloride, calcium-bicarbonate, magnesium-sulphate, and iron-carbonate (Mathess 1982).

5.4.3.2 Major ion and physical parameter assessment

The major ions in both gravel aquifers are Ca, Mg, Na, K, HCO_3, SO_4, and Cl, which typically constitute more than 90% of ions present in natural waters (Fetter 1994). Tables 5.3 and 5.4, and Figures 5.3 and 5.4, show summary statistics for the TTG and ETG Aquifers, and delineate sampling locations for the 1996 groundwater survey. Details of full chemical analyses are presented in Appendix H-III.

Variable levels of some major ions are encountered across the extent of the TTG and ETG Aquifers. Differences, however, are slight to moderate. Sample sites for the TTG Aquifer which display high ion concentrations compared to the mean are given in Table 5.5. Specific features present in the data are as follows:

- Three areas of the TTG Aquifer consistently yield elevated levels of various constituents. These are sites 8 and 19, 14 and 15, and 18.
- Generally regarded as conservative variables, chloride and sodium levels range from 2.4-16 g/m^3 and 2.7-6.7 g/m^3 in the TTG Aquifer, with elevated levels observed in three areas, at sites 8 and 19, 14 and 15, and 18. Little variation in chloride is observed in the ETG Aquifer (Table 5.4); sodium results are not available.

SUMMARY STATISTICS FOR MAJOR ION ANALYSIS - TAKAKA TOWNSHIP GRAVEL AQUIFER					
Variable	No of samples	Mean	Median	Maximum	Minimum
ph	8	6.5	6	8	6
Conductivity	8	13.6	12	26	11
Calcium	19	20.5	16	42	14
Magnesium	19	2.5	2.4	3.8	1.8
Sodium	8	3.8	3.7	6.7	2.7
Potassium	8	1.6	0.96	7.7	0.4
Chloride	19	5.7	4.9	16	2.4
Sulphate	8	6.6	5.6	15	2.8
Bicarbonate	8	55	52	74	43
Nitrate	19	1.9	1.4	6.8	0.82
Hardness	19	62	51	118	44

Table 5.3. Summary Statistics for major ion analysis, TTG (1996)

SUMMARY STATISTICS FOR MAJOR ION ANALYSIS - EAST TAKAKA GRAVEL AQUIFER					
Variable	No of samples	Mean	Median	Maximum	Minimum
Conductivity	5	17.8	18	23.9	12.5
Calcium	5	28	29	41	15
Magnesium	5	2	2	2.2	1.7
Chloride	5	4.6	4.7	5	4.1
Nitrate	5	1.9	1.7	2.9	1.5
Hardness	5	57	80	111	44

Table 5.4. Summary statistics for major ion analysis, ETG (1996)

ABOVE MEAN STATISTICS FOR TAKAKA TOWNSHIP SITES							
Site number	Calcium (20.1)	Magnesium (2.7)	Sodium (3.8)	Potassium (1.6)	Chloride (5.9)	Sulphate (6.6)	Bicarbonate (55)
4	23	2.9	*	*	*	*	70
7	*	*	*	*	*	7.8	*
8	42	2.8	*	*	9.5	*	*
13	*	*	*	*	*	7.3	*
14	*	*	*	*	6.8	*	*
15	*	*	*	*	6.2	*	*
18	31	3.8	6.7	7.7	16	15	74
19	41	3.4	*	*	11	*	*
20	35	*	*	*	*	*	*

mean values are given in parentheses

* indicates below mean, or not recorded values

Table 5.5. Above mean values for the TTG (1996)

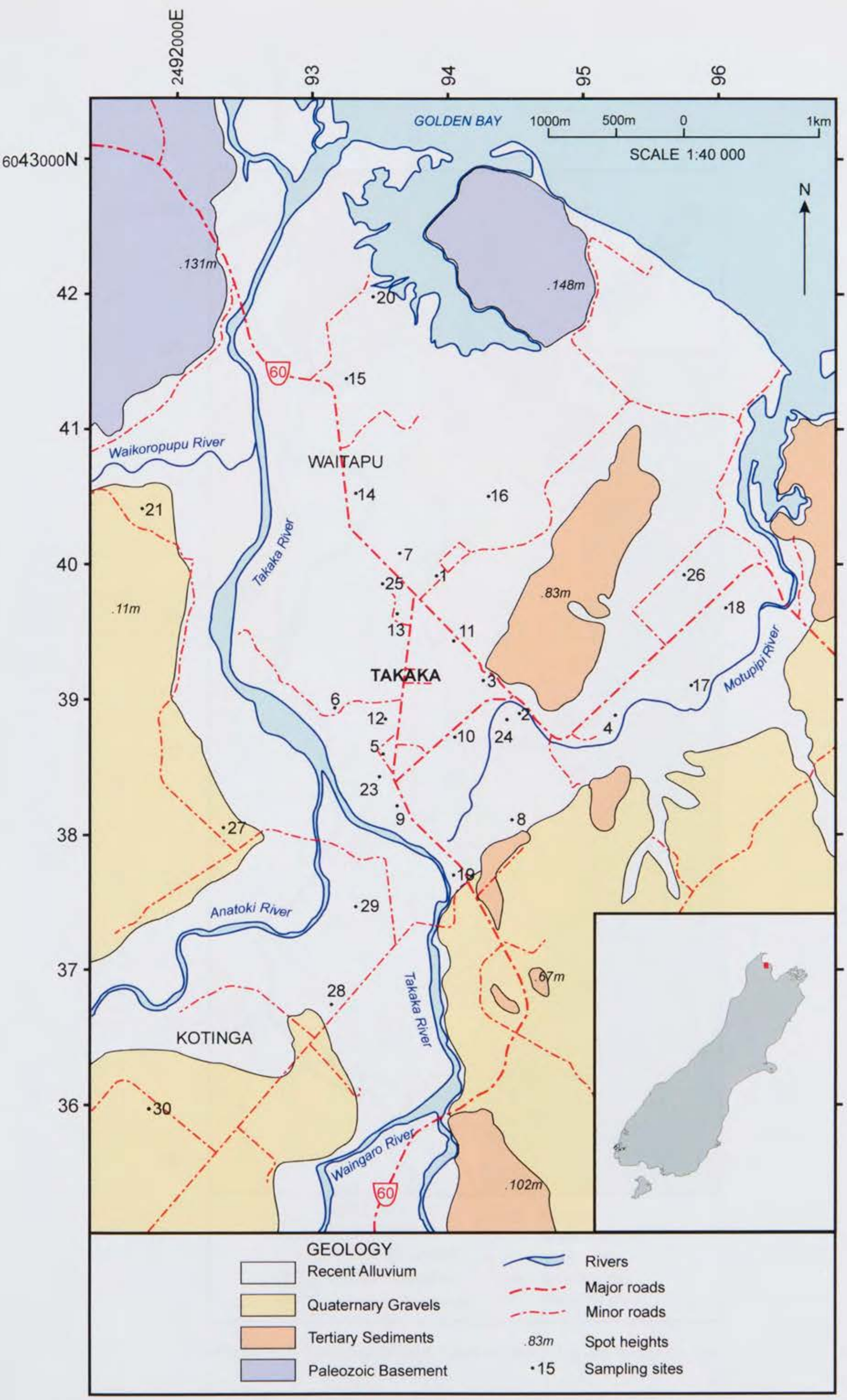


Figure 5.3. Location of Takaka Township Gravel Aquifer sampling sites (note: samples 20-29 involved in 1986 nitrate survey only)

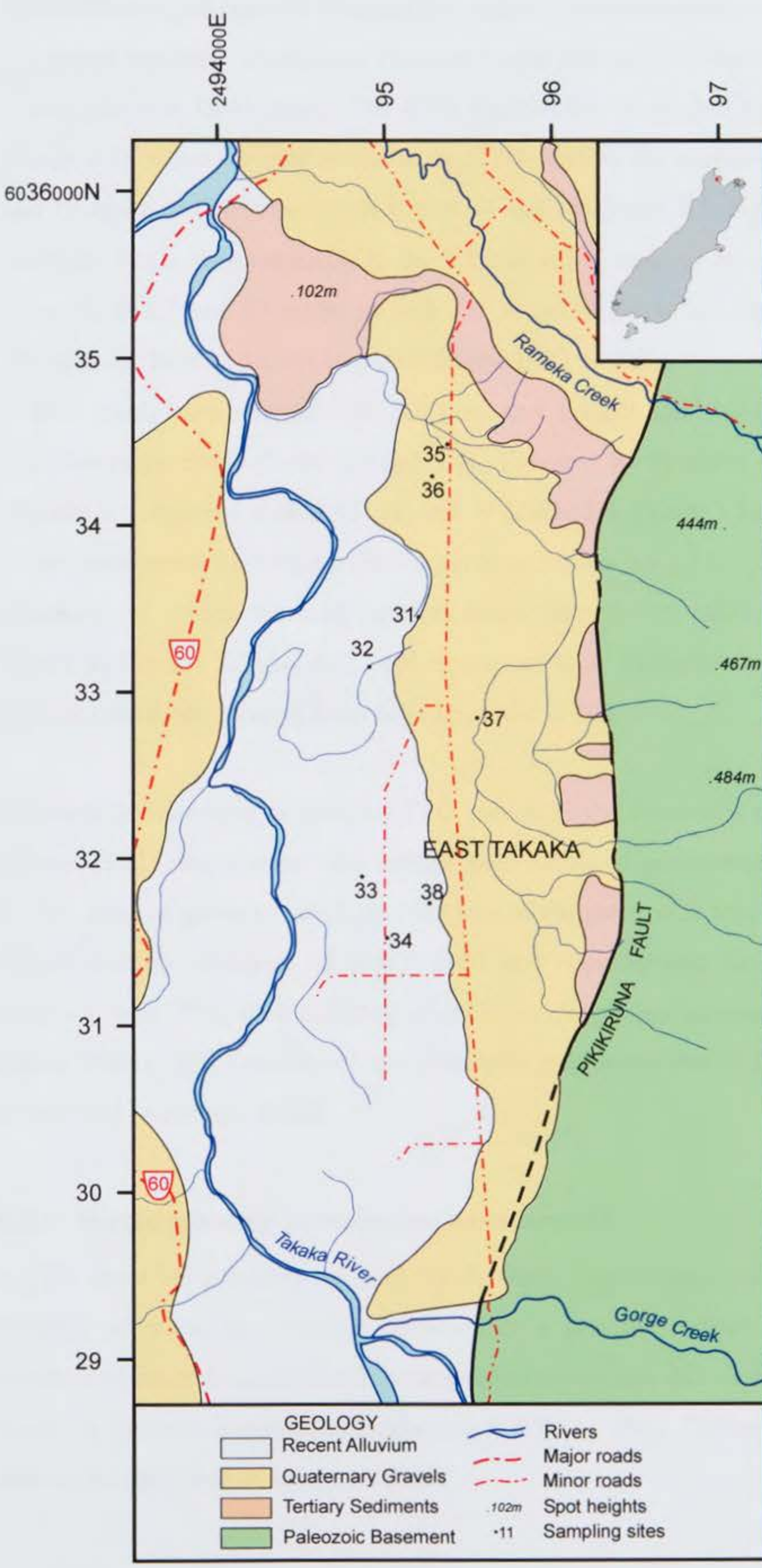


Figure 5.4. Location of East Takaka Gravel Aquifer sampling sites

- Similar spatial patterns are observed for calcium and magnesium distributions across the gravel aquifers. Respective calcium ranges for the TTG and ETG Aquifers are 14-42 g/m^3 and 15-41 g/m^3. The ETG Aquifer has the higher mean calcium value (Table 5.4), while elevated levels in the TTG Aquifer are encountered at sites 18, 8 and 19 again, and 20 (which is near sites 14 and 15) (Table 5.5, Figure 5.3).
- Sulphate levels vary markedly in the TTG Aquifer, ranging from 2.8-15 g/m^3. At sites 18, and 7 and 13 (near 14 and 15), elevated levels are recorded (Table 5.5, Figure 5.3). Results are not available for the ETG Aquifer.
- Nitrate levels vary between 0.82-6.8 g/m^3 and 1.5-2.9 g/m^3 for the TTG and ETG Aquifers respectively (Table 5.3 and 5.4). Elevated levels above 4 g/m^3 in the TTG Aquifer are observed at sites 17, 18, and 19 (Table 5.5, Figure 5.3). Further details of nitrate assessment for both aquifers is given in section 5.4.3.3 C.
- Conductivity values for both aquifers range from 11-26 mS/m (distributions are shown in Figures 5.5 and 5.6). pH figures are only available for the TTG Aquifer and are consistent, ranging from 6-8 (Appendix H-III).

A graphical presentation of selected TTG results in the form of a series of stiff plots (Matthess 1982) clearly shows the similar ionic nature of groundwater samples (Figure 5.7). All ions are given in meq/l, and the size of the patterns is approximately equal to the ionic content. Analyses of WWD 6601 and Pupu Springs have been plotted for comparison with TTG: their differing scales show the greatly increased ionic content of the karst waters. ETG results are not presented graphically due to the limited suite of ions analysed (Appendix H-III).

5.4.3.3 Water quality parameter assessment

The TTG and ETG Aquifers are used for domestic, agricultural, and industrial supply. Suitability of water for drinking purposes is a primary concern. There are two parameters of interest, namely microbiological contaminants and chemical determinands of health or aesthetic significance (following NZDWS 1995). Tables extracted from the standards are presented in Appendix H-III.

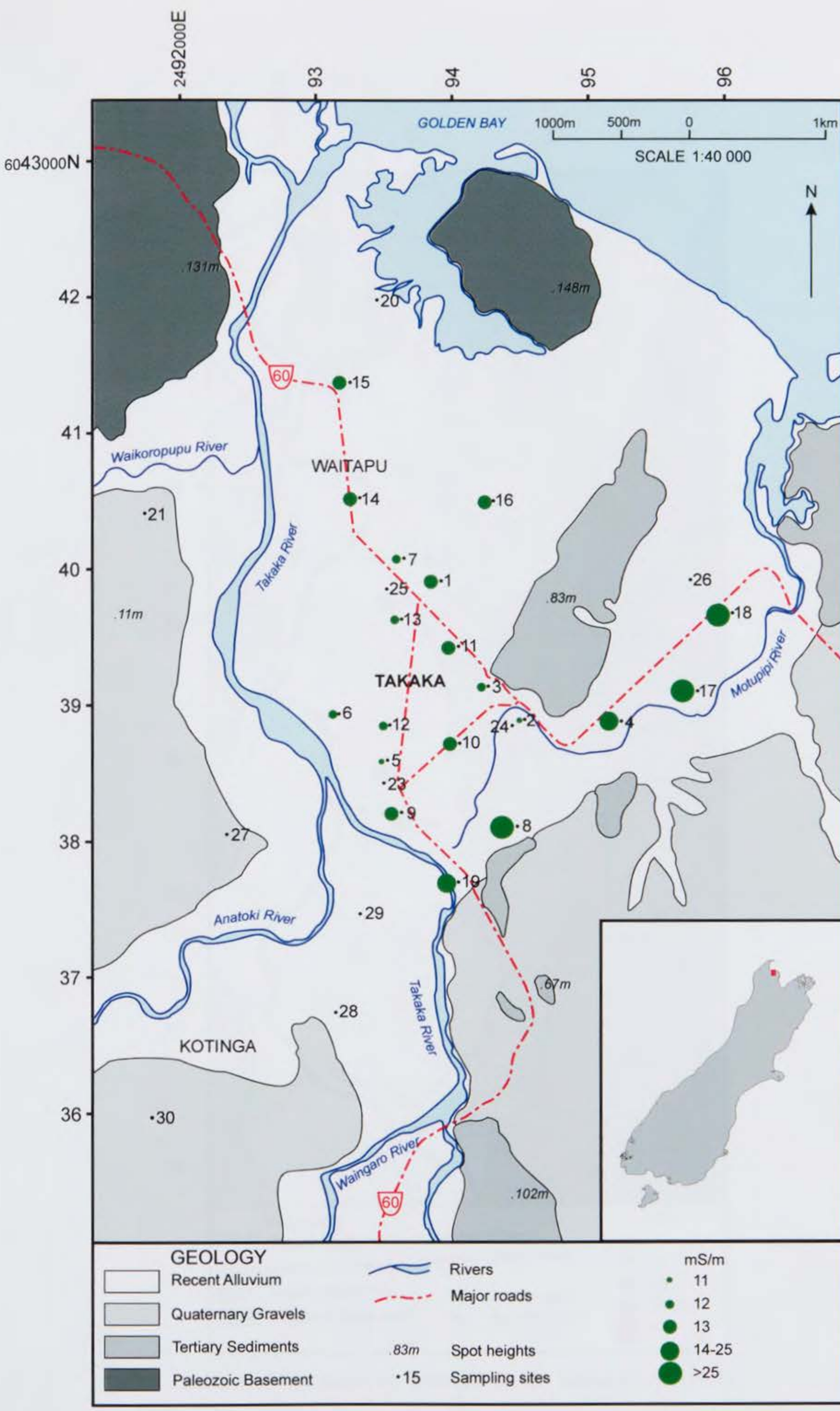


Figure5.5. Conductivity results for the Takaka Township Gravel Aquifer (1996)

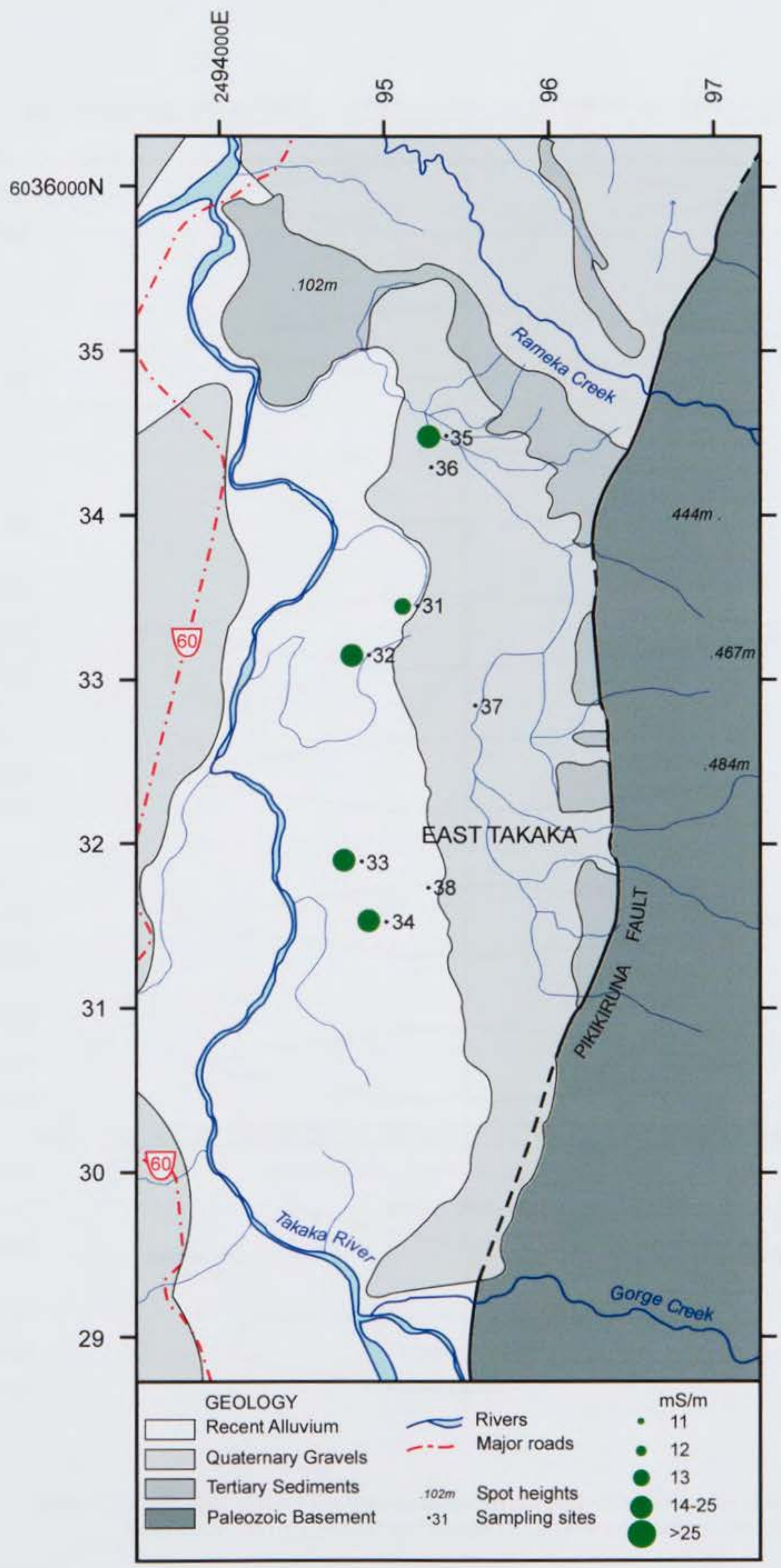


Figure: 5.6. Conductivity results for the East Takaka Aquifer (1996)

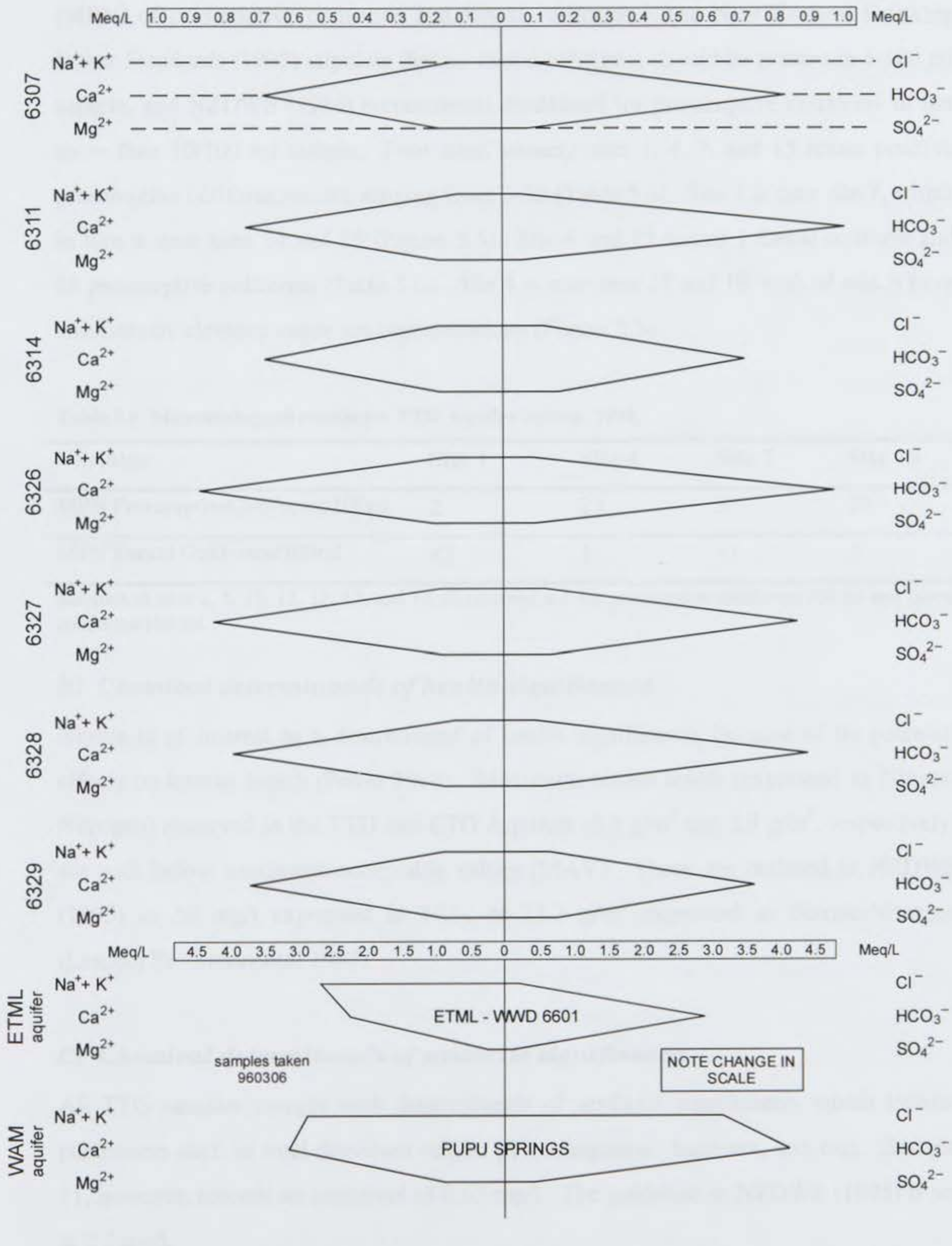


Figure 5.7. Stiff plots of the TTG Aquifer (selected samples - 960313), with additional plots of WWD 6601 (ETML) and Pupu Springs (WAM) for comparison (960306)

A) Microbiological contaminants

The 1996 survey of the TTG and ETG Aquifers counted the maximum probable number (MPN) of presumptive coliforms and faecal coliforms. The New Zealand Drinking Water Standards (1995) stipulate that no faecal coliforms should be present in a 100 ml sample, and NZDWS (1984) recommends guidelines for presumptive coliforms of not more than 10/100 ml sample. Four sites, namely sites 1, 4, 7, and 15 return positive presumptive coliform results, ranging from 3-32 (Table 5.6). Site 1 is near site 7, which in turn is near sites 14 and 15 (Figure 5.3). Site 4 and 15 record 1 faecal coliform and 23 presumptive coliforms (Table 5.6). Site 4 is near sites 17 and 18, both of which have consistently elevated major ion concentrations (Figure 5.3).

Table 5.6 Microbiological results for TTG Aquifer survey, 1996.

Variable	Site 1	Site 4	Site 7	Site 15
MPN PresumptiveColiforms/100ml	2	23	3	23
MPN Faecal Coliforms/100ml	<1	1	<1	1

Samples at sites 2, 5, 10, 11, 12, 13, and 16 all returned < 1 for presumptive coliforms/100 ml and faecal coliforms/100 ml.

B) Chemical determinands of health significance

Nitrate is of interest as a determinand of health significance, because of its potential effects on human health (Fetter 1994). Maximum nitrate levels (expressed as Nitrate-Nitrogen) observed in the TTG and ETG Aquifers (6.8 g/m^3 and 2.9 g/m^3, respectively) are well below maximum acceptable values (MAV). These are outlined in NZDWS (1995) as 50 mg/l expressed as NO_3, or 11.3 g/m^3 expressed as Nitrate-Nitrogen (Lincoln Environmental 1997).

C) Chemical determinands of aesthetic significance

All TTG samples comply with determinands of aesthetic significance, which include parameters such as total dissolved solids, pH, manganese, hardness, and iron. Sample 11, however, records an iron level of 0.65 mg/l. The guideline in NZDWS (1995) is set at 0.2 mg/l.

5.4.2.3 Interpretation of water chemistry and quality data

A) Water chemistry

Sources and potential sources of major ions together with other important parameters for both gravel aquifers are summarised in Table 5.7. Explanations of spatial distributions are as follows:

- As primary recharge sources, water from the Takaka River and rainfall contribute variable quantities of major ions to the TTG and ETG Aquifers. Chloride, sodium, magnesium, and sulphate ions are presumed to come (at least in part) from rainfall. Greater concentrations are observed in the TTG Aquifer, reflecting the composition of rainfall near the coast. Chloride levels in the TTG Aquifer are not indicative of seawater contamination. The composition of rainfall further inland (i.e. the rainfall recharge to the ETG Aquifer) changes, becoming a calcium sulphate/bicarbonate solution (Berner and Berner 1987).
- Nitrate concentrations in shallow aquifers (or parts of aquifers) which are recharged by rivers are expected to be low (Lincoln Environmental 1997), while in aquifers dominated by rainfall recharge, nitrate levels would typically fluctuate.
- Ionic variability across aquifers can be explained at least in part by the influence of aquifer material. As noted by Matthess (1982), shallow unconsolidated fluviatile-alluvial aquifers such as TTG and ETG sometimes display variable groundwater quality which can be exacerbated in shallow groundwater systems.
- Aquifer flow paths and high tranmissivity zones can account for observed decreases in certain ions, in particular chloride and sodium.
- Landuse and the influence of human activities can have a profound effect on water quality, in particular on the concentrations of nitrate, alkaline earth ions (Ca and Mg), and on conductivity. In the TTG Aquifer northeast of the Takaka River and township a zone has been identified incorporating sites 8, 17, 18 and 19 (Figure 5.3) which records higher than mean levels of conductivity (Figure 5.5), and of calcium, magnesium, and nitrate. Higher than mean levels in this zone have been attributed to diffuse and/or point source contamination from dairy farming and intensive land use. Loss to groundwater from the Motupipi River (a typically high ion, high conductivity, nutrient laden stream) would provide additional ions and nitrates.

	GRAVEL AQUIFERS TTG AND ETG	WWD 6601-ETML AQUIFER
POTASSIUM (gm^3)	Source: rainfall (cyclic salt, or part of terrestrial dust) Potential source: agricultural fertilisers	Source: rainfall (cyclic salt, or part of terrestrial dust) Potential source: agricultural fertilisers
SODIUM (gm^3)	Source: rainfall (cyclic salt or part of terrestrial dust), aquifer material (more prominent in coastal sections) Potential sources: inputs via various chemicals	Source: minor constituent of carbonate rocks, rainfall (cyclic salt or part of terrestrial dust) Potential sources: inputs via various chemicals
MAGNESIUM (gm^3)	Source: rainfall (cyclic salt, or part of terrestrial dust)	Source: rainfall (cyclic salt, or part of terrestrial dust), derivation from aquifer rocks.
CALCIUM (gm^3)	Source: small amounts atmospheric precipitation (cyclic salt, dust from calcereous rocks), aquifer material, surficial deposits Potential sources: fertilisers, human contamaination	Source: rainfall,Limestone aquifer rocks containing mixtures of other impurities, terrestrial dust Potential sources: fertilisers, human contamination
NITRATE (gm^3)	Sources: nitrogen compounds in rainwater (up to 2.5 mg3), use of nitrogen fertilisers, land application of organic wastes, localised liquid and solid wastes, animal wastes, can locally increase the supply of soluble nitrogend compounds	
SULPHATE (gm^3)	Source: atmospheric precipitation (cyclic salts, and as terrestrial dust), breakdown of organic substances Potential sources: addition from leachable sulphate in fertiliser, and from other human influences	Source: aquifer rocks (gypsum and anhydrite), atmospheric precipitation (terrestrial dust), breakdown of organic substances Potential sources: addition from leachable sulphate in fertiliser, and from other human influences
CHLORIDE (gm^3)	Source: rainfall (cyclic salt, or part of terrestrial dust), with maxiumum contribution at coast, decreasing inland Potential sources; seawater contamination, chloride containing fertilisers, or liquid/solid wastes	Source: small quantities derived from rainfall (terrestrial dust), local anomalies due to terrestrial and human causes Potential sources: seawater contamination near coast, chloride containing fertilisers, or liquid and solid waste
ALKAKINITY (gm^3)	carbonate and hydrogen carbonate ions primarily derived from atmosphere	measure of carbonate species present dertermined by aquifer rock and atmosphere
SILICA (gm^3)	weathering of silicate minerals in aquifer rocks, or surficial material	

Variable proportions of undertermined ions will be contributed to gravel aquifers from interaction from unconsolidated fluviatile materrial.
Silica is a nonionic species.
Alkalinity is a measure of bicarbonate species present.

Table 5.7. Sources and potential sources of major constiuents of the TTG, ETG, and ETML Aquifers

B) Suitability of groundwater for domestic and agricultural supply

All TTG and ETG groundwater samples comply with NZDWS (Ministry of Health 1995) and are deemed suitable to drink without treatment, except those from sites 4 and 15, both recording one faecal coliform (sourced most likely from proximal septic tank systems). Nitrate levels are below NZDWS.

Groundwater is deemed suitable for livestock and irrigation. Sodium Adsorption Ratios (SAR) are calculated for selected sites in the TTG Aquifer. These determine the degree to which sodium in irrigation water replaces the adsorbed Ca and Mg in soil clays, thus damaging soil structure (Hounslow 1995, Matthess 1982, Richards 1969). As expected (due to the nature of aquifer materials) the salinity hazard and sodium hazards are low and pose no problems. Results and full details of procedures are presented in Appendix H-IV. Analysis is not performed for the ETG Aquifer due to lack of sodium data.

C) Case study : Nitrate assessment

Nitrate is an important parameter for assessment, particularly for the Tasman District Council's groundwater resource management programme. Nitrate enters the shallow unconfined ETG and TTG Aquifers by leaching through soil. Nitrate and nitrogenous compounds are sourced primarily from the atmosphere. Additional potential sources include diffuse inputs from grazed pasture, cropland-fertiliser application, dairying, increased irrigation, and effluent irrigation (i.e. meatworks, dairy factory waste), and point inputs from effluent spills and input of waste products.

1996 and 1986 nitrate results (expressed as Nitrate-Nitrogen) are presented in Table 5.8, and distributions are shown in Figure 5.8. The 1996 survey incorporates 24 sites which range from 0.46-6.8 g/m^3 Nitrate-Nitrogen. The mean value of the TTG Aquifer (1.9 g/m^3) is typical of levels which could be derived from atmospheric contributions (Matthess 1982). Two areas on the outskirts of the Takaka township, in the farming areas of Motupipi and Waitapu, record higher than mean values (Figure 5.8). The highest value of 6.8 g/m^3 is recorded at site 18, a shallow well located adjacent to the Motupipi River in a dairy farm paddock (Figure 5.8). The ETG Aquifer nitrate results are fairly consistent (Table 5.8).

SUMMARY OF NITRATE DETAILS FOR 1996, 1986 SURVEYS OF GRAVEL AQUIFERS IN THE TAKAKA VALLEY					
TAKAKA TOWNSHIP AND SURROUNDS					
13 March 1996			***25 -26 Mar 1986***		
Site no	**WWD**	**Nitrate (g m^3)**	**Site no**	**WWD**	**Nitrate (g m^3)**
1	WWD 6305	1.6	20	WWD 6003	1.9
2	WWD 6307	0.48	15	WWD 6009	2.6
3	WWD 6308	1.2	21	WWD 6005	5.1
4	WWD 6310	1.6	22	WWD 6114	0.044
5	WWD 6311	0.46	23	WWD 6321	0.36
6	WWD 6312	1.1	24	WWD 6306	0.3
7	WWD 6314	2	25	WWD 6313	1.4
8	WWD 6324	3.1	26	WWD 6403	4.1
9	WWD 6325	1.1	27	WWD 6505	1.6
10	WWD 6326	0.7	28	WWD 6511	2.9
11	WWD 6327	1.4	29	WWD 6503	3.8
12	WWD 6328	1.4	30	WWD 6513	3
13	WWD 6329	1.2			
14	WWD 6005	2.3			
15	WWD 6009	0.82			
16	WWD 6101	2.5			
17	WWD 6401	6.8			
18	WWD 6402	3.3			
19	WWD 6611	1.9			

EAST TAKAKA					
13 March 1996			***25 -26 Mar 1986***		
Site no	**WWD**	**Nitrate (g m^3)**	**Site no**	**WWD**	**Nitrate (g m^3)**
31	WWD 6804	2.9	36	WWD 6801	2.3
32	WWD 6816	2	37	WWD 6806	3.4
33	WWD 6819	1.7	39	WWD 6810	1.9
34	WWD 6820	1.6			
35	WWD 6824	1.5			

Table 5.8. Comparison of 1986 and 1996 nitrate results for the TTG and ETG Aquifers
Full site details are presented in Appendix H-III

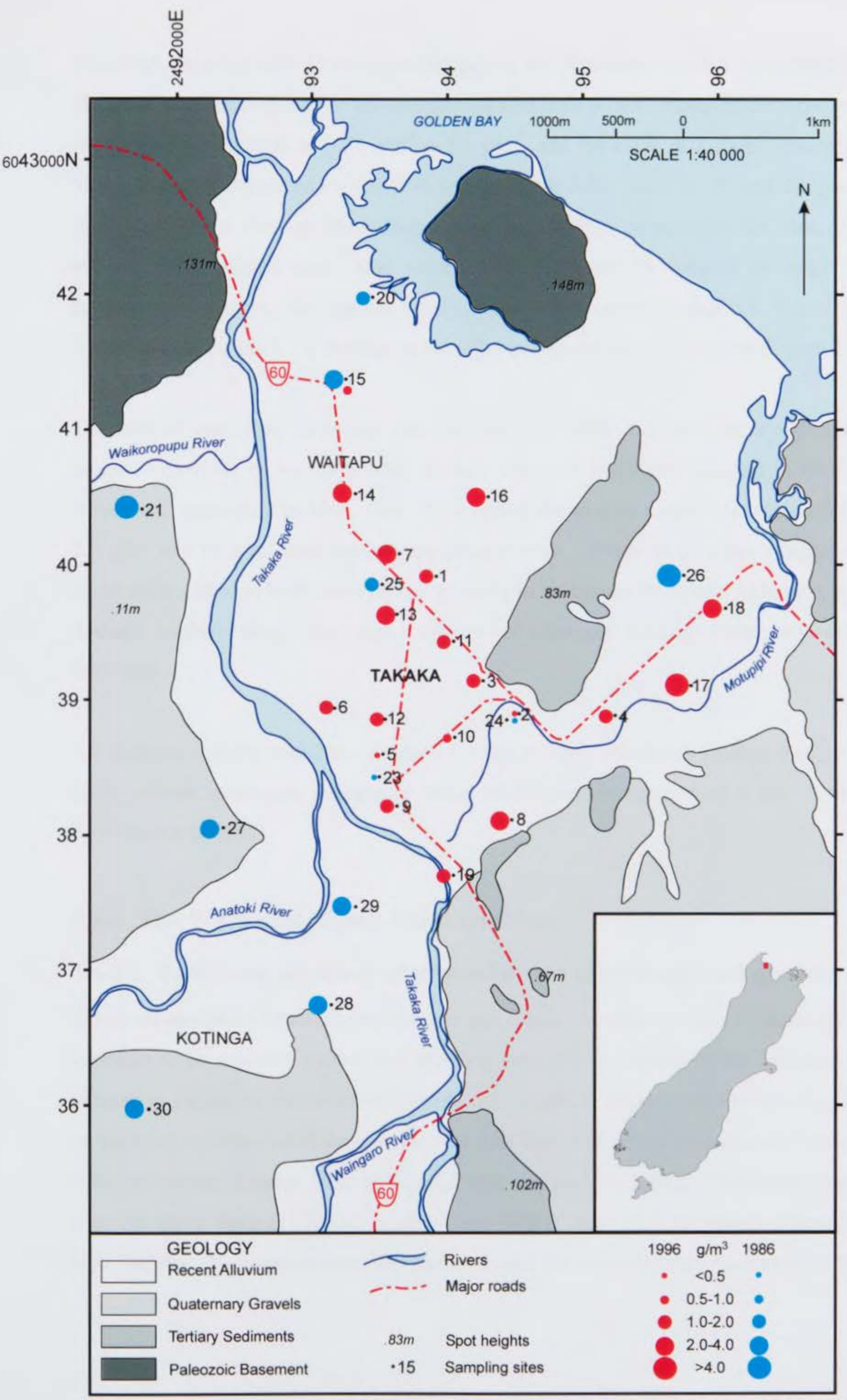


Figure 5.8. Nitrate plots for 1986 and 1996 surveys, Takaka Township Gravel Aquifer

The 1986 sampling sites in the township region are distributed around the periphery of the TTG Aquifer, with half of the samples located west of the Takaka River. The range in recorded values is from 0.04 g/m^3 to 5.1 g/m^3, and the mean is 2.2 g/m^3 (marginally higher than that calculated for the 1996 survey, Table 5.8). Sites 28, 29, and 30 (located at the end of the Kotinga Plains surrounded by kiwifruit cropping at the time of the survey) record higher than mean values. Sites 21 and 26, located on dairy farm properties, record the two highest results of the 1986 survey (Table 5.8, Figure 5.8). Nitrate results for the ETG Aquifer in the 1986 survey are fairly consistent (Figure 5.9).

The lack of consistent sampling sites between the 1986 and 1996 surveys precludes direct comparison of survey results, as only one well originally sampled in the 1986 survey was resampled in 1996. Site 15 records a decrease in nitrate concentration from 2.6 g/m^3 to 0.82 g/m^3 over the two sampling periods. When an area has a higher than mean nitrate level in both surveys, this is likely to be caused by human influence, either through landuse (dairy farming), or input of nitrogen bearing waste products or fertilisers.

All samples comply with New Zealand Drinking Water Standards (Ministry of Health 1995) whose maximum acceptable value of Nitrate-Nitrogen is 11.3 gm^3 (Lincoln Environmental 1997).

5.4.3 The WAM and ETML karst aquifers

5.4.3.1 Temporal analysis of groundwater chemistry and quality

Temporal analysis of data allows changes and trends in concentrations of water quality variables to be assessed, either over the long term (i.e. the length of the data base), or short term (i.e. on an annual or seasonal basis). Analysis of water quality and chemistry of the karst aquifers involves a seven year data base comprised of 3-monthly samples, collected by the Tasman District Council and analysed by IGNS. Designated sample sites are Main Springs (WAM Aquifer) and WWD 6601 (ETML Aquifer) located at N26 946366. 29 measurements are included, and the available data base extends from

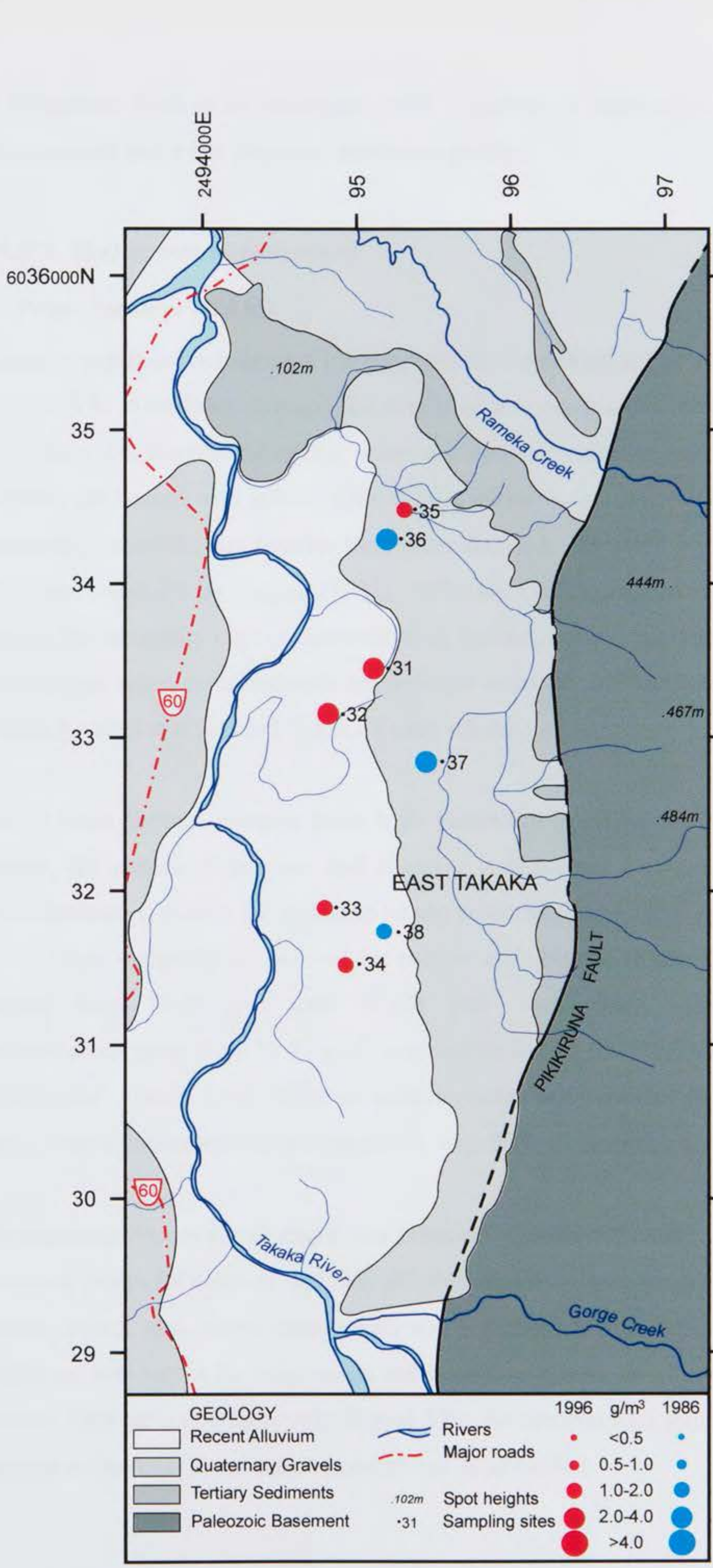


Figure 5.9. Nitrate plot for 1986, 1996 surveys, East Takaka Gravel Aquifer

26 September 1990 to 23 September 1997. Analysis is designed to provide baseline assessment of major ion chemistry and water quality.

5.4.3.2 Major ion assessment

A) Pupu Springs (WAM)

Summary statistics for important ion concentrations recorded at Pupu Springs are shown in Table 5.9. Additional ions and full details of analyses are presented in Appendix H-III. Major constituents of spring water are sodium, chloride, calcium, magnesium, sulphate, potassium, and silica. Nitrate is a minor constituent, while traces of iron, manganese, bromide, and fluoride have been detected. As noted by Michaelis (1976), and commented on by Rapier (1975), Williams (1977), and Mueller (1991), Pupu Springs has unusually high concentrations of sodium, potassium, magnesium, chloride, and sulphate, when compared with the principal recharge sources (water from the Upper Takaka River (Table 5.1) and Takaka Valley rainfall).

The 29 Pupu Springs samples show high variability in major ion concentrations. In general, the pattern of increase and decrease is consistent between major ions, and, while distinctive, it does not appear to fit any seasonal pattern from year to year (Figure 5.10). Most variability is observed for sodium and chloride (Figure 5.11), with values ranging from 32-76 g/m^3 and 45-121 g/m^3 respectively. Measured calcium concentrations range from 51-73 g/m^3, magnesium from 3-9.6 g/m^3, and potassium from 2.2-6.1 g/m^3 (Table 5.9). Sulphate concentrations are variable, ranging from 10-20 g/m^3. Nitrate concentrations are consistent, with 96% of samples less than 0.5 g/m3.

The maximum values for all major ions coincide with the November 1990 sample. The minimum values for calcium, sodium, and chloride levels coincide with the March 1997 sample, which also shows magnesium and potassium levels well below the mean. Additional low values for magnesium and potassium are recorded in the July 1992 and October 1995 surveys respectively (Figure 5.9). No obvious long term trend (i.e. overall increase or decrease in ion concentration) can be identified.

SUMMARY STATISTICS FOR MAJOR IONS OF PUPU SPRINGS AND ETML AQUIFER *29 surveys included, conducted between 26 Sept 1990 - 23 Sept 1997*						
Variable	**WAM**			**ETML**		
(gm3)	**Mean**	**Maximum**	**Minimum**	**Mean**	**Maximum**	**Minimum**
Chloride	93.55	121	45	6.4	13.5	4
Sulphate	16.26	20.2	10.4	3.9	6	2.2
Silica	6.46	7.5	4	10.4	14	8
Nitrate	0.66	0.32	0.902	2.2	4.04	1.7
Alkalinity	203.03	229	183	132.2	154	110
Sodium	57.9	75.7	32.2	4.8	5.2	4.3
Potassium	4.59	6.1	2.2	0.8	1.7	0.3
Calcium	62.83	73.4	51.4	43	50	37
Magnesium	7.92	9.6	3	2.8	3.3	2.4

Table 5.9. Summary statistics for the major ions of Pupu Springs and WWD 6601 (ETML)

SUMMARY STATISTICS FOR PHYSICAL PROPERTIES OF PUPU SPRINGS AND ETML AQUIFER *29 surveys included, conducted between 26 Sept 1990 - 23 Sept 1997*						
Variable	**WAM**			**ETML**		
	Mean	**Maximum**	**Minimum**	**Mean**	**Maximum**	**Minimum**
pH	7.71	8.35	7.5	7.6	8.2	7.1
Conductivity (ms/m)	64	77	36	24	27	22

Table 5.10. Summary statistics of physical properties of Pupu Springs (WAM) and WWD 6601 (ETML)

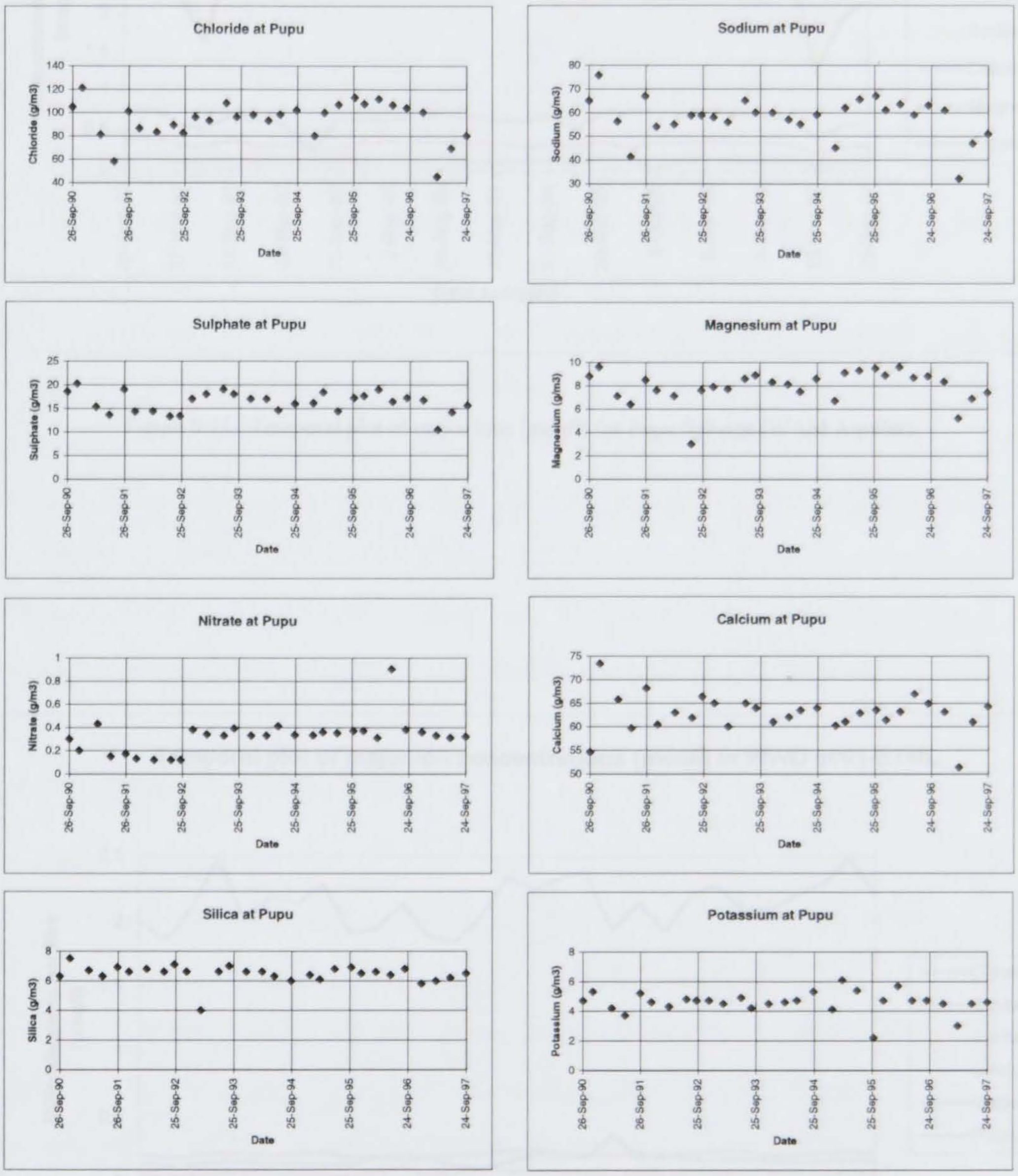


Figure 5.10. Temporal variation in major constituents of Pupu Springs (1990-1997). All figures quoted in g/m^3. Samples collected approximately every 3 months

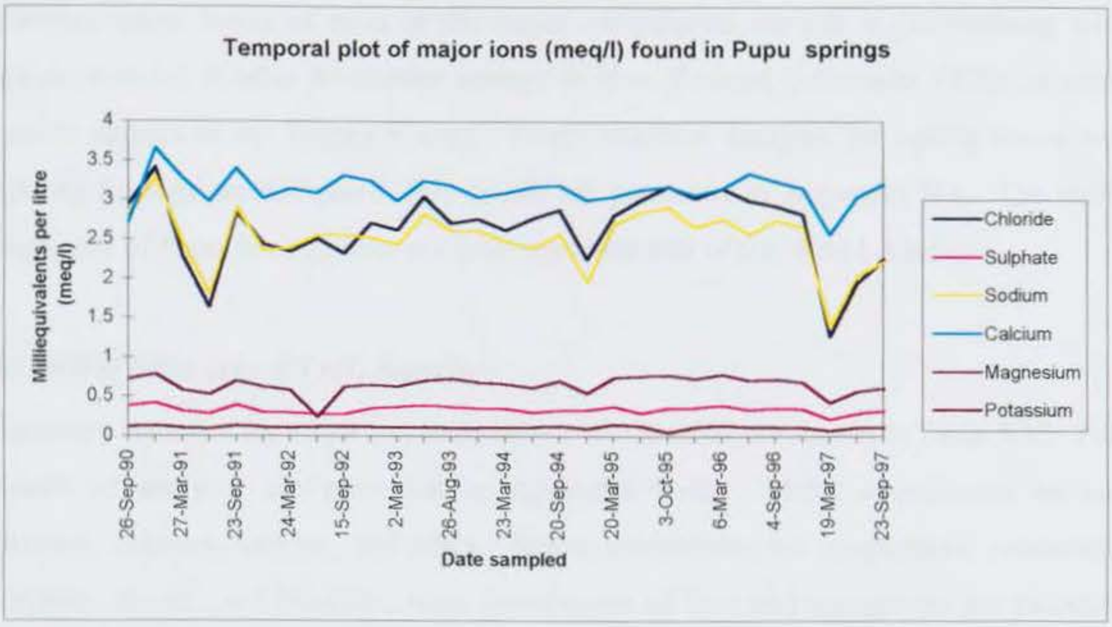


Figure 5.11. Temporal plot of major ions (meq/l) for Pupu Springs (WAM Aquifer)

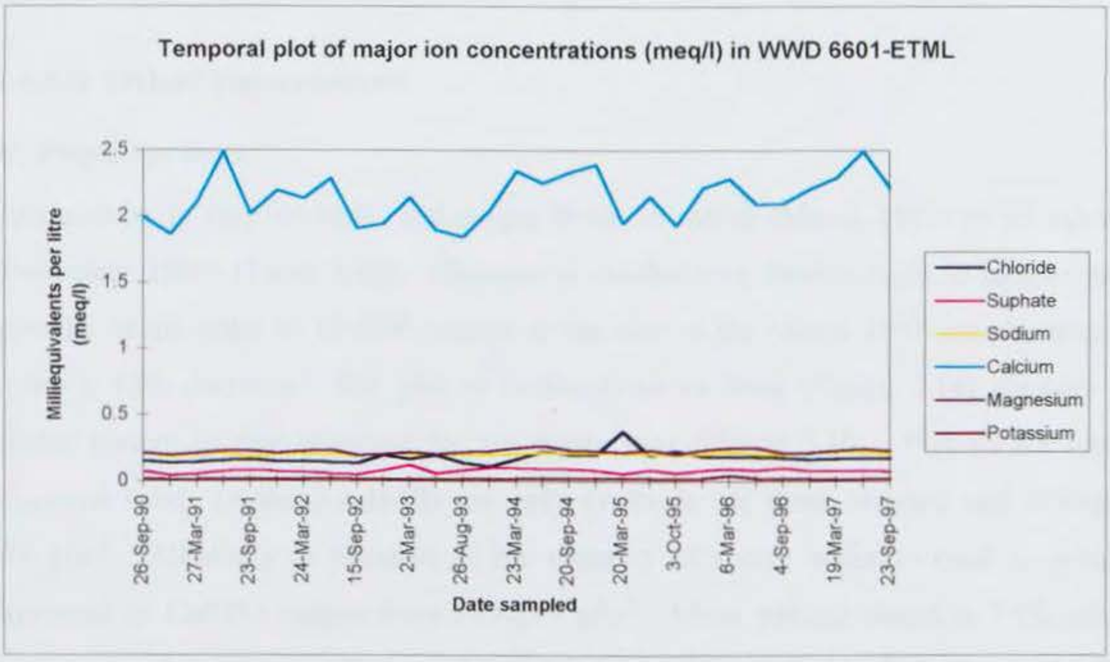


Figure 5.12. Temporal plot of major ions (meq/l) for WWD 6601 (ETML Aquifer)

Elevated mean levels of most of the major constituents are not in concordance with levels recorded at other freshwater springs in New Zealand (Michaelis 1976), or other marble springs in the Takaka Valley. Single chemical analyses for Spring Brook and Spittals Springs are compared; full details are presented in Appendix H-I. The water chemistry of Pupu Springs does not fully represent that of the WAM Aquifer.

B) WWD 6601 (the ETML Aquifer)

Summary statistics for major ion analyses for WWD 6601 are shown in Table 5.10. Full details of analyses are presented in Appendix H-III. Major constituents include chloride, calcium, sodium, and silica. Minor constituents are magnesium, potassium, sulphate, nitrate, and bromide; trace constituents of iron and manganese are recorded (Appendix 5). High variability is observed in calcium concentrations (Figure 5.12), which range from 37-50 g/m^3, with a mean of 43 g/m^3 (Table 5.9). No obvious seasonal pattern can be detected. More subdued variation is observed for other major cations and for nitrate (Figure 5.12, 5.13). Conspicuous highs are apparent in the chloride and nitrate records in March 1995 (13.5 and 4.04 g/m^3 respectively) and in potassium records in March 1996 (1.7 g/m^3). Sulphate concentrations range from 2.2-6.4 g/m^3.

5.4.3.3 Other parameters

A) Pupu Springs

Conductivity is very variable, and ranges from 36 mS/m (March 1997) to 77 mS/m (November 1990) (Table 5.10). Changes in conductivity from sample to sample are typically of the order of 15-20%, except in the case of the March 1997 sample, which shows a 45% decrease. The plot of conductivity vs. time (Figure 5.14) displays a similar pattern to that observed for the major ions (Figure 5.10). Figures for total dissolved solids (Appendix H-III) are only available for three samples and average 479 g/m^3. Alkalinity (a measure of the capacity of spring water to react to acids, expressed as $CaCO_3$) ranges from 183-229 g/m^3. Mean pH calculated is 7.71, with maximum and minimum values of 7.7 and 8.5 respectively (Table 5.10, Figure 5.14). Alkalinity and pH display a scattered and variable response over time.

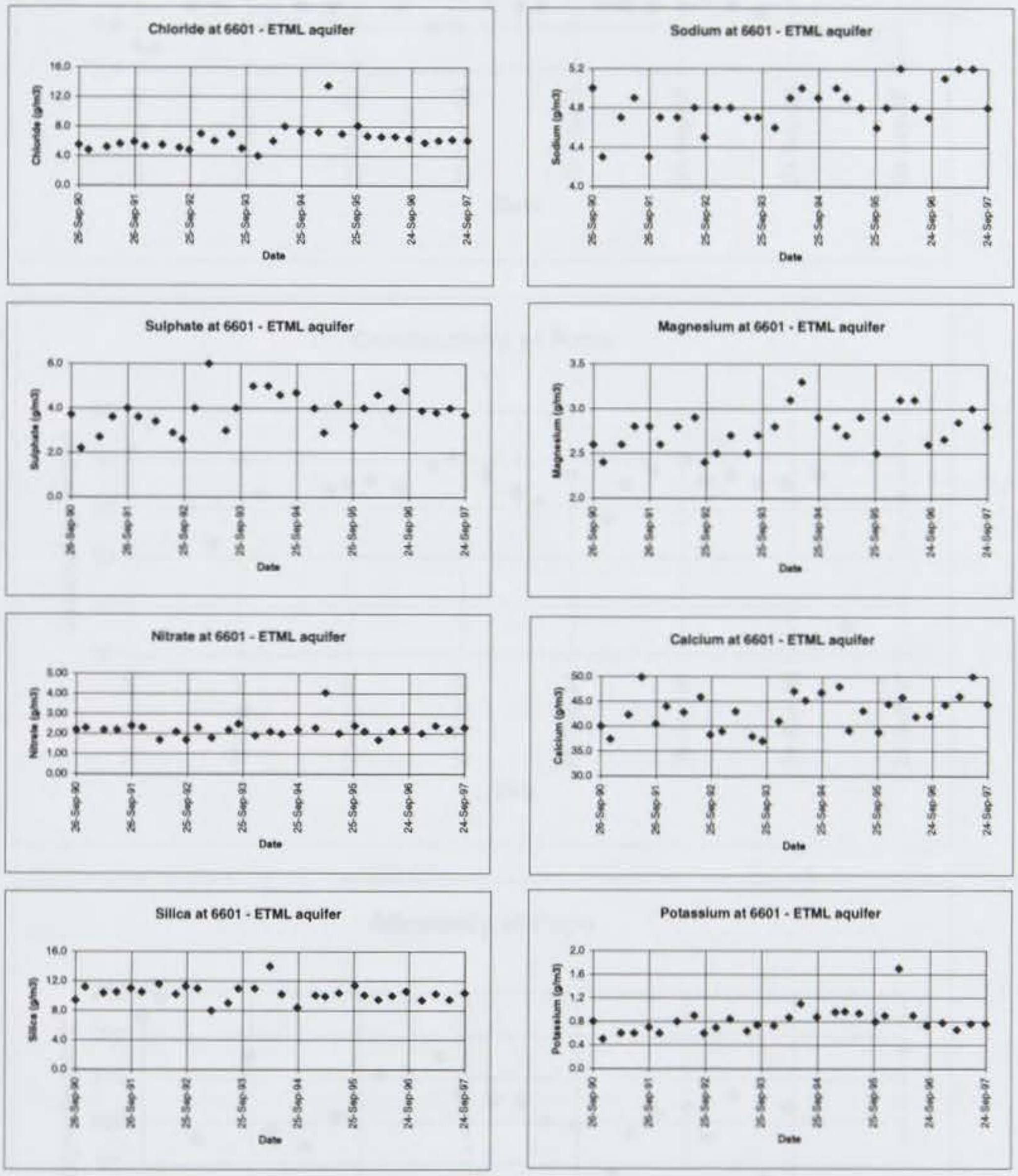


Figure 5.13. Temporal variation in major constituents of WWD 6601-ETML Aquifer (1990-1997). Samples collected approximately every 3 months

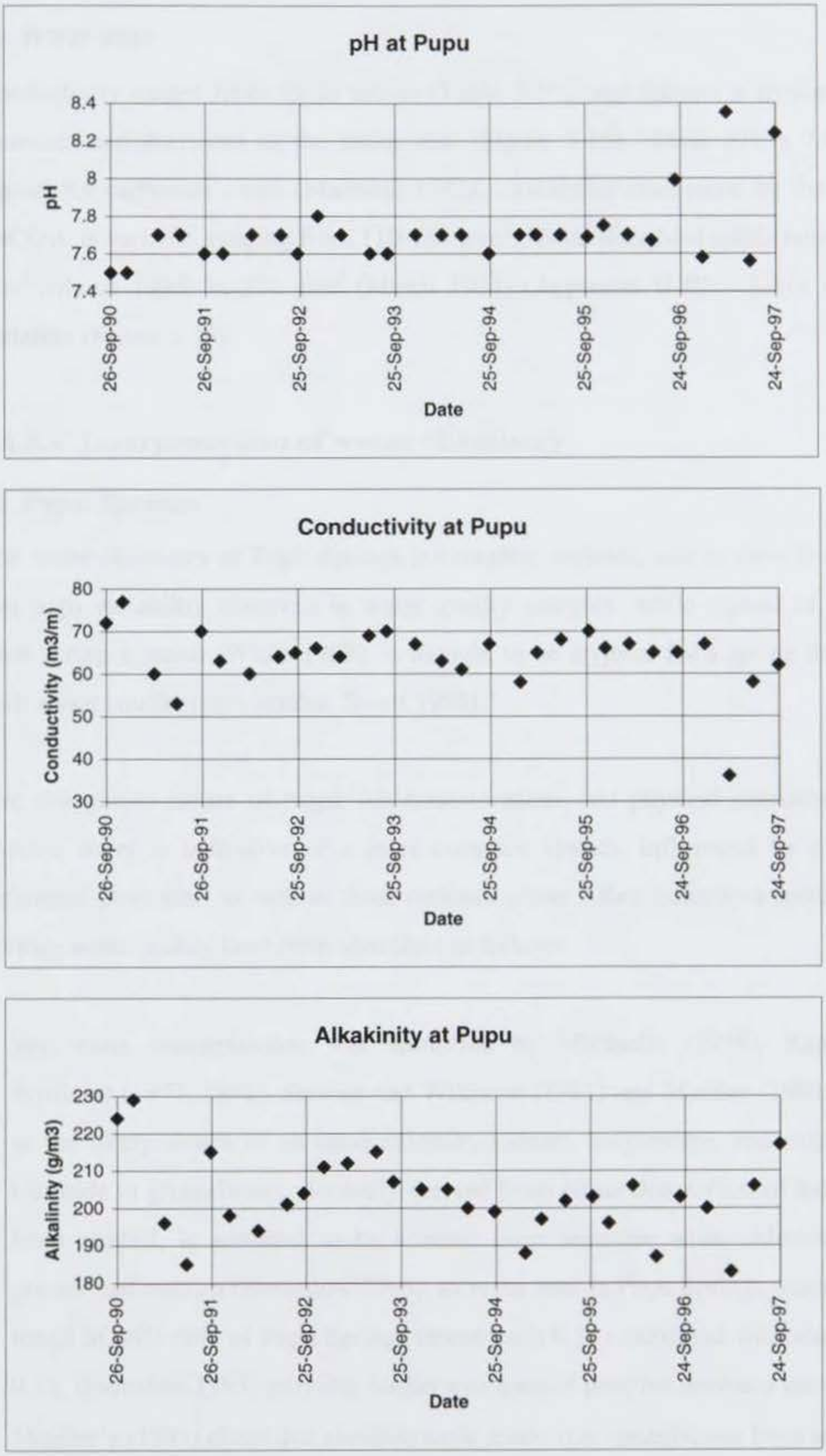


Figure 5.14. Temporal variation in physical properties of Pupu Springs

B) WWD 6601

Conductivity ranges from 22-27 mS/m (Table 5.10), and follows a similar pattern of increases and decreases as the major ions (Figure 5.15). Mean pH is 7.6, which is typical for carbonate rocks (Matthess 1982). Alkalinity (measured by the amount of $CaCO_3$), is variable, ranging from 110-154 g/m^3. Total dissolved solids range from 188 g/m^3 (March 1995) to 238 g/m^3 (March 1994) (Appendix H-III). Silica shows little variation (Figure 5.13).

5.4.3.4 Interpretation of water chemistry

A) Pupu Springs

The water chemistry of Pupu Springs is complex, variable, and extremely changeable. The high variability observed in water quality analyses, while typical of conduit-fed karst spring systems (White 1988), is thought to be atypical for a spring that is fed by such a vast aquifer (pers. comm. Smart 1998).

The changeable nature of major ion concentrations and physical parameters of Pupu Springs water is indicative of a more complex system, influenced by a number of additional processes, as well as those outlined above. Key influences specific to Pupu Springs water quality have been identified as follows:

- Sea water contamination was identified by Michaelis (1976), Rapier (1975), Williams (1977, 1992), Stewart and Williams (1981) and Mueller (1989,1991,1992) as the likely source of elevated chloride, sodium, magnesium, and sulphate levels. Chloride in groundwater, normally derived from either dissolution of halite rocks or from rainfall, is assumed to be sourced from seawater when chloride levels are greater that sodium (Hounslow 1995), as is the case in Pupu Springs water. A similar meq/l SO_4/Cl ratio of Pupu Springs (mean ratio 0.13) compared with seawater (ratio 0.15, Hounslow 1995) provides further evidence of possible seawater contribution.
- Mueller's (1991) claim that elevated ionic levels (i.e. contribution from seawater) are indicative of a direct conduit connection to the sea (i.e. offshore) is disputed. It is equally possible that a complex arrangement of a conventional diffusion/mixing process of seawater occurs, and if so, diffusion would be variable (under different

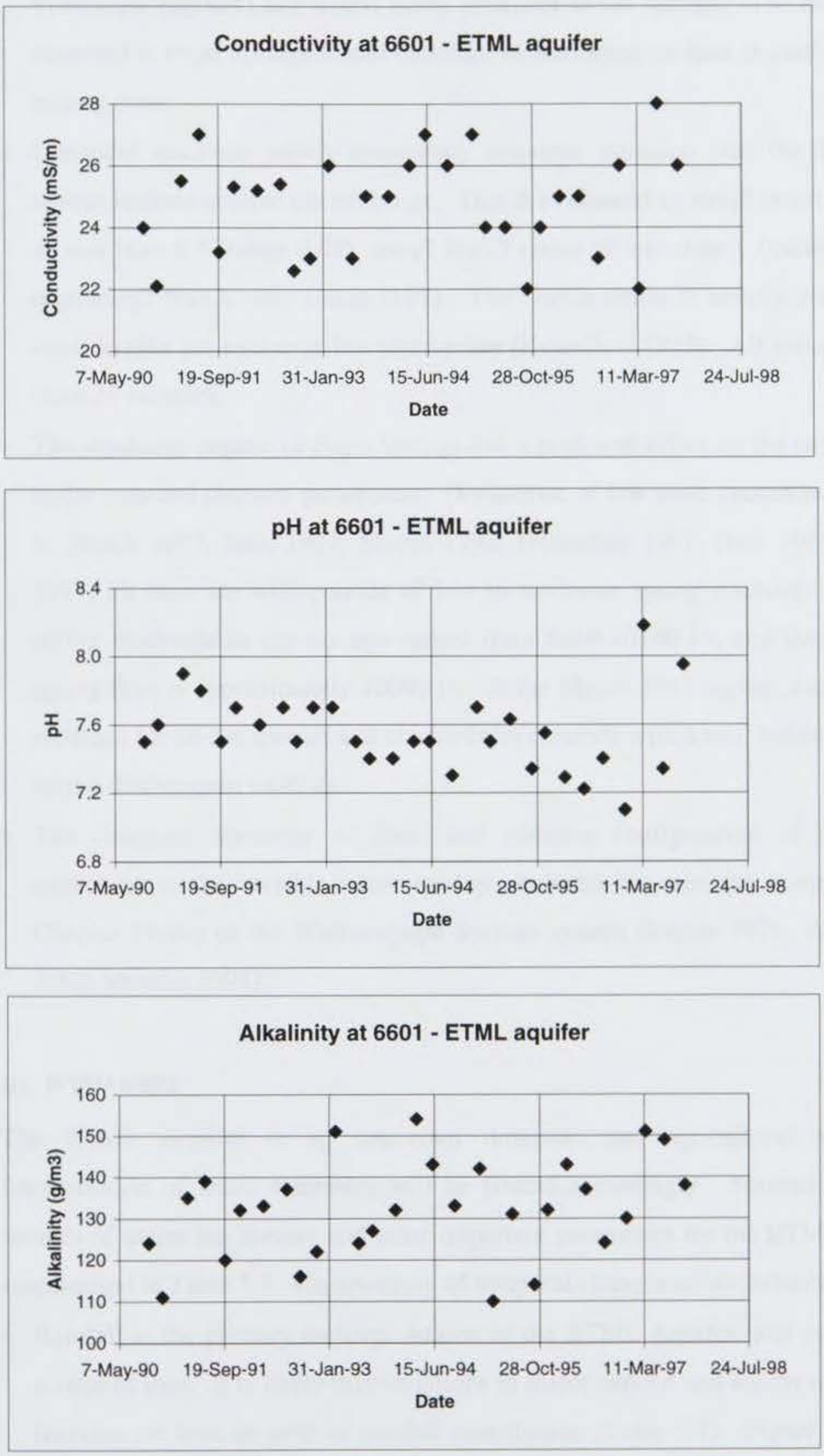


Figure 5.15. Temporal variation in physical parameters of WWD 6601

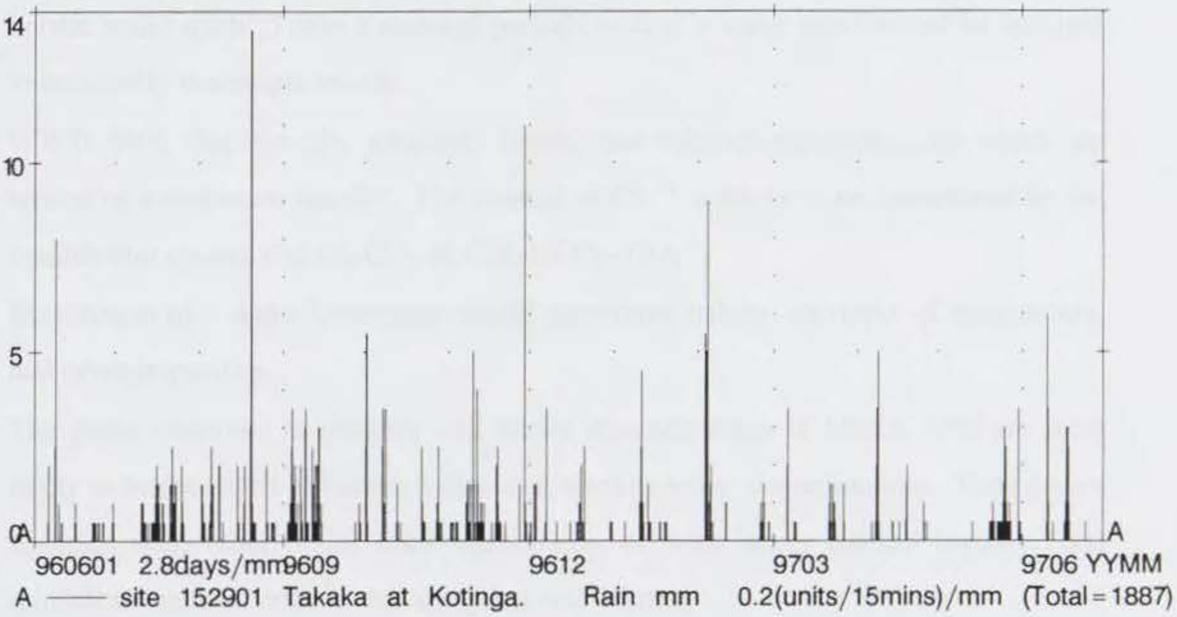
hydrologic regimes) and would occur proximal to the springs. The high variability observed at Pupu Springs would therefore be attributed (at least in part) to a complex mixing zone.

- Chemical reactions which accompany seawater intrusion into the Pupu Springs system include reverse ion exchange. This is evidenced by meq/l ratios of Na/Na+Cl of less than 0.5 (mean 0.48), meq/l Na/Cl ratios of less than 1 (mean 0.96), and a high meq/l Na/Ca ratio (mean 0.81). The Na/Ca ration is usually very low unless considerable ion exchange has taken place (Hounslow 1995). All means are derived from 29 samples.
- The discharge regime of Pupu Springs has a profound effect on the concentration of major ions and physical parameters. Occurrence of low ionic concentrations (such as in March 1997, June 1997, March 1992, December 1991, June 1991, and March 1991) all coincide with periods of low to moderate spring discharge. The overall spring discharge in the surveys ranges from 6449-10140 l/s, and the mean overall spring flow is approximately 10000 l/s. In the March 1997 survey, minimum values recorded for all ion species and conductivity coincide with a well below mean overall spring discharge of 6449 l/s.
- The structure, hierarchy of flow, and complex configuration of spring outlets contribute to the variable water quality observed between the components (refer Chapter Three) of the Waikoropupu Springs system (Rapier 1975; Williams 1977, 1992; Mueller 1991).

B) WWD 6601

The ETML Aquifer is an important domestic and agricultural water supply. Interpretation of water chemistry will be treated accordingly. Sources and potential sources of major ion species and other important parameters for the ETML Aquifer are summarised in Table 5.7. Explanations of temporal changes are as follows:

- Rainfall is the primary recharge source of the ETML Aquifer, and is an important source of ions. It is likely that variations in major cations and anions over time are a function (at least in part) of rainfall contribution (Table 5.7). Figure 5.16 shows a series of plots (including selected ions, silica levels, and alkalinity) for the ETML Aquifer, and representative rainfall data, from June 1996 to June 1997. It is obvious



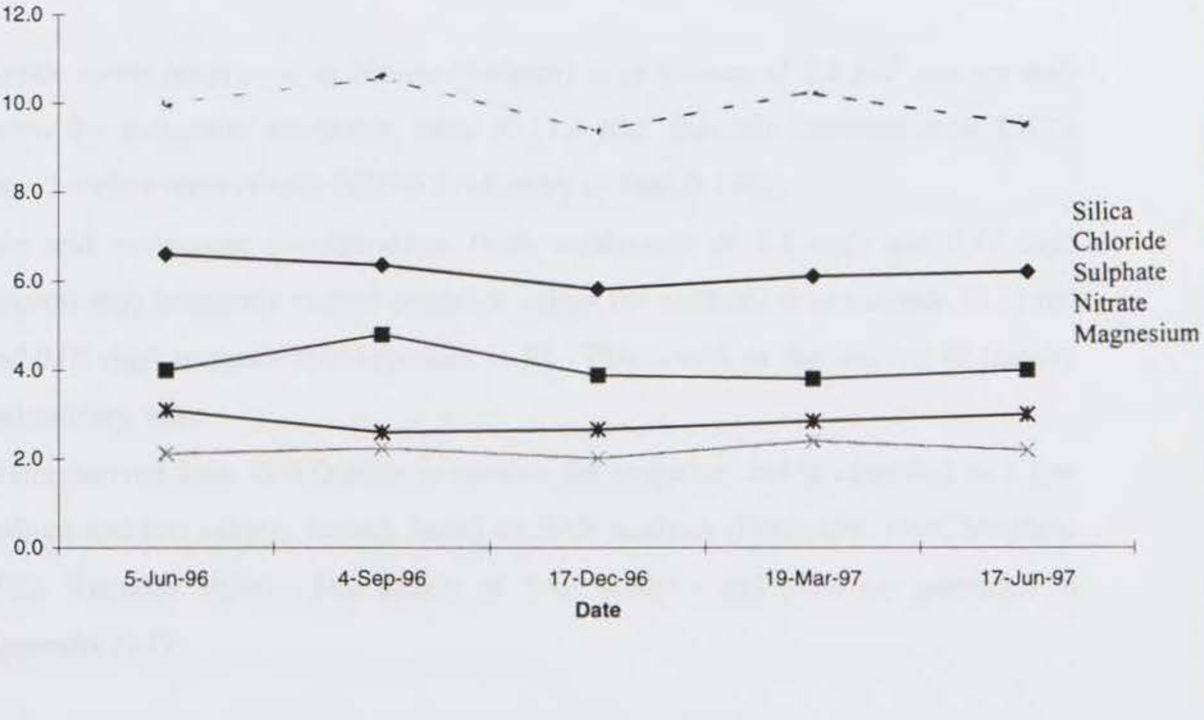


Figure 5.16. Chemograms and rainfall input of the June 1996 to June 1997 water quality sampling runs

that 3-monthly samples are inadequate to determine any relationship between the variations in water chemistry and rainfall patterns. Weekly monitoring (as employed by Lastennet and Mundry 1997 in a recent study of the relationship of rainfall and karstic water quality) over a selected period (such as a water year) would be required to accurately determine trends.

- WWD 6601 displays pH, alkalinity levels, and calcium concentrations which are typical of a carbonate aquifer. The content of Ca^{2+} is likely to be determined by the equilibrium system $CaCO_3$-CO_2-H_2CO_3-HCO_3- CO_3^{2-}.
- Dissolution of Takaka Limestone would contribute calcite, mixtures of magnesium, and other impurities.
- The peaks observed in chloride and nitrate concentrations in March 1995 are most likely to be the result of human influences, such as waste contamination. They do not coincide with other major ionic maximums, or with heavy rainfall input. Total rainfall seven days prior to this sampling was 20 mm.

Details of the suitability of water for drinking and agricultural supply are given below. Discussion is restricted to chemical analysis, as microbiological results are not available.

- Nitrate levels (expressed as Nitrate-Nitrogen) have a mean of 2.2 gm^3 and are well below the maximum acceptable value of 11.3 g/m^3 (Lincoln Environmental 1997); they therefore comply with NZDWS (Ministry of Health 1995).
- Iron and manganese concentrations (with maximums of 2.1 mg/l and 0.12 mg/l respectively) frequently exceed guideline values for aesthetic determinands (0.2 mg/l and 0.05 mg/l respectively)(Appendix H-II). This results in the staining of laundry and sanitary ware.
- Water derived from WWD 6601 is suitable for irrigation and is classified as a low sodium and low salinity hazard, based on SAR analysis (Hounslow 1995, Matthess 1982, Richards 1969). Full details of SAR analysis and plots are presented in Appendix H-IV.

5.5 FUTURE MONITORING REQUIREMENTS

5.5.1 Karst aquifer monitoring

The concentration of major ions and pollutants in karst water systems can vary dramatically with time. Conventional groundwater monitoring, which consists of analysis of water samples collected quarterly, semi-annually or annually, may be invalid in many karst systems; the data sets generated can be irrelevant for management purposes (Quinlan and Alexander 1987). Quinlan and Alexander (1987) proposed an improved monitoring procedure for karst systems in which conduit flow and concentrated recharge were important. This required hourly sampling of springs and relevant wells to be taken during storm or runoff events. Sampling should continue well past the hydrograph peak, and during the last part of the recession at 4-6 hourly intervals. This data would then be compared with the regular samples taken during stable flow periods throughout the year (such as the present 3-monthly sampling programme at Pupu Springs). Reliable assessment or characterisation of karst water quality could then be made.

Pupu Springs is only one of a limited number of sites in the NGMP with over 5 years of data. Ongoing monitoring of WAM is of utmost importance if changes or trends in water quality are to be established early. Monitoring in addition to the existing 3-monthly programme is necessary for accurate characterisation of water quality. Recharge events in particular require intensive monitoring: This results in an improved understanding of recharge, storage, and discharge of WAM. Short term analyses can then be compared with the existing long term records.

Intensive monitoring of WWD 6601 (ETML) may not be as appropriate, as recharge in the ETML Aquifer is primarily derived from diffuse sources. The existing programme takes 3-monthly samples, without due regard for hydrological conditions. Samples should be obtained in stable periods, or in periods of low flow, in order to obtain representative results (McCarthy and Shevenell 1998). There may be merit in including analysis of additional sites, such as Motupipi Springs, and additional wells. Hydrogeological investigation is required to ensure that wells intersected the major flow paths or subterranean streams.

Management must implement a regular monitoring system of boreholes in the ETML Aquifer near the coast, ideally quarterly or bi-annually. There must be early identification of any areas prone to saltwater intrusion. Specific management plans must then be put into action. These would include the immediate reassessment of borehole spacing, and a review of the total level of allowable abstraction in the section of the aquifer nearest to the coast.

5.5.2 Gravel aquifer monitoring

Regular annual sampling of the shallow gravel aquifers in the Takaka Valley would build on the existing minimal data and would establish a useful working data base. Wells used in the 1996 TTG and ETG surveys would provide the initial data set; they would then need to be resampled for comparisons. The surface water assessment should coincide with the groundwater sampling. Appropriate timing of the sampling, together with the evaluation of the antecedent rainfall, flow and groundwater conditions, must be considered. In order to establish seasonal water quality cycles, a minimum of six 2-monthly samples would be required (Hoare and Rowe 1992). It would also be necessary to have samples which represented a diverse suite of flow and groundwater conditions (i.e. high and low).

As with the ETML Aquifer, there must be specific monitoring of the gravel aquifer near the coast. Early intervention is needed if there is any evidence of saltwater intrusion. Well spacing and allowable abstraction must then be reassessed.

5.6 SYNTHESIS

A knowledge of surface water chemistry is needed before embarking on studies of groundwater chemistry, because of recharge relationships.

- TDC currently undertakes a 3-monthly sampling programme of WAM and ETML. There is no established ongoing monitoring scheme for TTG or ETG.
- Surface water shows elevated nitrate levels down the mainstem of the Takaka River as a result of land use. This is of concern.

- One area of the TTG Aquifer is identified as having consistently elevated ionic levels (in particular nitrate).
- Most TTG and ETG groundwater samples comply with NZDWS and are deemed suitable for drinking
- Continued monitoring of both TTG and ETG is required to build up a temporal database. The zone identified with elevated nitrates require particular vigilance.
- The analysis of groundwater chemistry of WAM is complex and very variable. WAM contains elevated ionic content, some of which is attributable to seawater contamination. This is of concern.
- The analysis of groundwater chemistry of ETML is typical of karst limestone groundwater. Results are moderately variable and there are some indications of water degradation. It is deemed suitable for drinking.
- Karst systems require specific monitoring programmes.
- Pupu Springs needs additional extensive monitoring to establish its chemical response to storm input events.

CHAPTER SIX : WATER RESOURCE EVALUATION OF THE TAKAKA RIVER AND THE TAKAKA VALLEY AQUIFER SYSTEM

6.1 INTRODUCTION

The final chapter of this thesis selects two aspects of surface and groundwater which are deemed pertinent to the water resource management of the Takaka Valley.

Firstly, a water balance for the Waikoropupu Arthur Marble Aquifer is presented. This offers a strong interpretation of the existence of submarine springs as part of the Waikoropupu Arthur Marble aquifer system. In management of water resources, an acceptance of clearly outlined assumptions and data limitations (both of which are inherent in any water balance) is considered valid. A water balance offers quantitative information which can initiate a better understanding of water issues.

Secondly, a preliminary assessment is made of the hydrological effects of the Cobb hydroelectric scheme, both on the Takaka River and on the Waikoropupu Arthur Marble Aquifer. Many unsubstantiated claims have been made as to the influence Cobb has on river flow and recharge downstream. There have been no previous studies of the quantitative hydrological impact of the Cobb dam, and Chapter Six seeks to redress this.

The human impact on the Takaka River and the Waikoropupu Arthur Marble Aquifer is profound; enlightened and effective water resource management must take this into account.

6.2 WATER BALANCE PRINCIPLES

A groundwater balance provides an order of magnitude estimate of reserves and storage changes for a specific aquifer or for an entire catchment. It is fundamental to the management of a groundwater resource. A water balance can be developed from a groundwater perspective or from a study of surface streams. The groundwater approach deals with the relationship between groundwater recharge and discharge processes. The following equation can be used to describe ΔS, the change in storage:

$$\Delta S = Q_R - Q_D \tag{6.1}$$

where Q_R = sum of inputs/inflows into a groundwater system

Q_D = sum of outputs/ouflows from groundwater system

Ford and Williams (1989) present a more complex equation:

$$\Delta S = P - E \pm R \pm U \tag{6.2}$$

where ΔS = change in storage of groundwater, soil moisture, channels, and reservoirs

P = precipitation

E = evapotranspiration

R = difference between outgoing stream flow and inflow

U = difference between groundwater outflow (–) and inflow (+)

The surface stream approach is a more classical approach to water balance analysis, and is represented by the following equation (Ford and Williams 1989):

$$Q = P - E \pm \Delta S \tag{6.3}$$

where Q = runoff

P = precipitation

E = evapotranspiration

$\pm \Delta S$ = withdrawl from or replenishment of storage

The change in groundwater storage (ΔS) is governed by one of three conditions.

- If inflow into the ground system is equal to discharge (or outflow) from that system, groundwater storage remains constant.

- If inflow into the ground system exceeds outflow, groundwater storage will remain constant while flow at any natural springs will increase.
- If outflow into the ground system is greater than inflow, groundwater storage will be depleted and will decrease.

In either approach the water balance can be performed over an annual period (e.g. a hydrologic year, from wet season to wet season), or over any specified period of time. Choosing a longer time period does not guarantee a more accurate model. In fact, the construction of any balance model at best involves a great deal of estimation and educated guesswork, even when an extensive data base is available (as is the case in the Takaka Valley).

6.3 WATER BALANCE FOR THE WAIKOROPUPU ARTHUR MARBLE AQUIFER

6.3.1 Previous estimates for the WAM Aquifer water balance

Preliminary estimates for the WAM Aquifer water balance were presented by Mueller (1987) and refined in Mueller (1992). Inputs were estimated at 66 m^3s^{-1} and were made up of stream flow and precipitation. Average discharges for the Takaka River and Waikoropupu Springs were estimated at 40-45 m^3s^{-1} and 15 m^3s^{-1} respectively. The resultant 8-9 m^3s^{-1} was attributed to submarine spring discharge (Mueller 1992).

The high level of estimation and unacceptable error levels in Mueller's water balance, together with the existence of new additional data records from 1992 to the present, warrants that a new groundwater balance model for the WAM Aquifer be attempted.

6.3.2 Methodology adopted

Two alternative water balance methods are employed to deduce the WAM Aquifer water balance, based on equations (6.1) and (6.3) (section 6.2). Method one, the annual water balance method, is based on a mean annual period, and uses precipitation data as the primary input source. Method two, the flow water balance, has been calculated over varying specified time periods, and is concerned solely with flow inputs. Both methods are primarily concerned with assessing change in storage.

6.3.3 Method One : Annual water balance

The annual water balance is calculated to the Kotinga recorder in the Takaka River (N26 939323) using mean annual figures for precipitation and flow inputs, and mean annual river and spring outputs. Relevant data manipulation is presented in the following section. Additional processing of raw data is presented in Appendix I.

The annual water balance is governed by the following equation:

$$\Delta S = (P_I + Q_I) - Q_D \tag{6.4}$$

where ΔS = change in storage

P_I= precipitation input

Q_I = sum of inflows

Q_D = sum of groundwater and surface water outflows

6.3.3.1 Annual water balance components

P_I, the precipitation input to the WAM Aquifer, is calculated for the Central Takaka Valley and the Waitui subcatchments, which together cover a total area of 241 km^2 (Section 1.2). It uses the following relationship:

$$[\text{Precipitation input}] = [\text{net precipitation}] \times [\text{infiltration }\%] \tag{6.5}$$

Precipitation input is defined as the amount of precipitation which contributes to the groundwater system over a given area. Net precipitation is the difference between the total precipitation and the estimated evapotranspiration.

Total precipitation is estimated at 2606 $mmyr^{-1}$, using the areal isohyetal method. Computation details are given in Appendix D-II. Evapotranspiration is estimated at 700 mm, based on values from the Riwaka climate recorder. Net precipitation is then calculated as 1906 $mmyr^{-1}$. Percentage infiltration is estimated to be as high as 80%. This is because of the predominance of fractures, joints, and sink holes on Arthur Marble cropping out on the Pikikiruna slopes and plateau, and because of the relatively thin permeable gravel cover overlying the WAM Aquifer in the river flats, terraces, and channels. Over the contributing area of 241 km^2 the precipitation input (P_I) is estimated as 1620 $mmyr^{-1}$, or 13.14 $m^3 s^{-1}$ (Table 6.1).

Q_I, the sum of inflows to the WAM Aquifer, is comprised of flow inputs from the Upper Takaka and Waingaro subcatchments, as measured by Harwoods and Hanging Rock recorders respectively. These results are used as an alternative to isohyetal precipitation estimations because of the limited rainfall data available; there are only four rainfall sites in the combined catchment area of 471 km^2. Mean annual figures (presented in Tables 6.1, 6.2) are calculated for the period from 1992 to 1996; the number of gaugings performed over this interval produces acceptable ratings, hence good quality data (pers. comm. M Doyle 1997). The estimated contribution from the Upper Takaka River is 15.42 m^3s^{-1} and from the Waingaro River is 19.95 m^3s^{-1} (Tables 6.1, 6.2).

The Anatoki River discharge is not included in the input calculations as the balance is being done to Kotinga, which is upstream of the Anatoki River-Takaka River confluence. Any contribution from the Anatoki River to the WAM Aquifer system would be negligible anyway (refer section 3.2.3.3), and so is not included in the final balance.

Q_D ,the total outflow or discharge from the WAM Aquifer, is comprised of two components. These are Takaka River flow, as measured by the Kotinga recorder, and total Waikoropupu Springs discharge (Appendix F-I, II). Mean annual discharge for the Takaka River at Kotinga is 35.70 m^3s^{-1}. Mean annual total spring discharge of Waikoropupu Springs is estimated at 13.25 m^3s^{-1} (Tables 6.1, 6.2).

Table 6.1 Mean annual inputs and outputs for the WAM Aquifer water balance, as derived by annual water balance. Units are m^3s^{-1}.

SOURCE	INPUT (m^3s^{-1})	SOURCE	OUTPUT (m^3s^{-1})
Upper Takaka	15.42	Waikoropupu Springs	13.25
Waingaro	19.95	Takaka River	35.70
Central and Waitui	13.14		
TOTAL	48.51	TOTAL	48.95

The mean annual input and output figures for the WAM Aquifer are presented in Table 6.2.

Table 6.2. Mean annual input and output figures for the WAM Aquifer. Units are $m^3yr^{-1} \times 10^6$

SOURCE	INPUT	SOURCE	OUTPUT
Upper Takaka	485	Waikoropupu Springs	417
Waingaro	627	Takaka River	1123
Central and Waitui	413		
TOTAL	1525	TOTAL	1540

6.3.3.2 Water Balance Calculations

Using equation 6.4, $\Delta S = (P_I + Q_I) - Q_D$

$$= (13.14 + 35.37) - 48.95$$

$$\underline{\Delta S = -\,0.44\ m^3s^{-1}}$$

From section 6.2 it follows that a deficit in a water balance is indicative of storage being depleted. It is assumed that the error for ΔS is in the region of $\pm$ 1 m^3s^{-1} (pers. comm. Doyle 1997). Taking this error into account, the WAM Aquifer is therefore relatively balanced. This refutes the existence of an 8-9 m^3s^{-1} excess which was attributed to submarine springs (Mueller 1992, Williams 1992). The existence of submarine springs is examined in greater detail in sections 3.3.5.

6.3.4 Method Two : Flow water balance

The flow water balance uses mean inputs (Q_I) and mean outputs (Q_D) over specified periods of time (ranging from four to eleven months). As with method one, the four flow balances are calculated to the Kotinga flow recorder site on the Takaka River (N26 939323).

Using equation (6.1), the flow water balance is given as follows:

$$\Delta S = Q_I - Q_D$$

$$\text{or} \qquad \Delta S = (Q_H + Q_W + Q_{C+R}) - (Q_P + Q_K) \qquad (6.5)$$

where ΔS= change in storage

Q_H = flow input from the Upper Takaka subcatchment

Q_W = flow input from the Waingaro subcatchment

Q_{C+R} = flow input from the Central Takaka Valley and Waitui subcatchments

Q_P = flow discharge from Waikoropupu Springs

Q_K = flow discharge from the Takaka River

6.3.4.1 Flow water balance components

Four data periods (A - D) are selected from a total data range of 941101 - 970701 (the date format is yymmdd). The time periods are as follows:

A	941104 - 950625
B	950619 - 951220
C	960102 - 961112
D	970122 - 970704

Data set requirements are as follows:

1. The records are of at least three months duration.
2. The start and finish times have the same Waikoropupu Springs discharge.
3. There are no major gaps in the data sets.
4. There is minimal overlapping or subsetting of data.

Requirements 1 and 2 are applied in order to remove or alleviate the influence of fluctuating storage. Requirements 3 and 4 avoid reproduction of results.

Mean flow input values are derived for the Upper Takaka, Waingaro, Central Takaka Valley and Waitui subcatchments. Flow recorders and their representative areas are presented in Table 6.3. Mean output values are derived for Takaka River discharge (Q_K) and Waikoropupu Springs discharge (Q_P); specifications are presented in Table 6.4. Mean flow figures for Q_H and Q_W over specified time periods are generated using the pdistribution command (pdist) on TIDEDA programme. Mean flow values for the Central Takaka Valley and Waitui subcatchments involve considerably more manipulation of data.

Table 6.3. Flow input sites used to represent the surface flow input into the Takaka Valley.

FLOW INPUT SITE	REPRESENTATIVE AREA
Q_H - Harwoods @ Takaka river	260 km^2 - Upper Takaka subcatchment (Cobb)
Q_W - Waingaro @ Hanging Rock	211 km^2 - Waingaro subcatchment
Q_C - Rameka @ Pages Cut	203 km^2 - Central Takaka Valley subcatchment
Q_R - Riwaka @ South Branch	38 km^2 - Waitui subcatchment

Table 6.4. Flow output sites used to represent the river discharge and total spring discharge from the WAM Aquifer.

OUTFLOW SITE	REPRESENTATIVE AREA
Q_K - Kotinga @ Takaka River	Represents the flow output from 712 km^2 of the Takaka Catchment
Q_P - Waikoropupu Springs	Discharge figures are of total spring output

The mean flow input (in l/s) for the Central Takaka Valley subatchment is estimated, using weighted mean flow data from the Rameka at Pages Ford recorder. The Rameka Catchment above the recorder has an area of 2.7 km^2. Raw data of the mean flow (l/s) from Rameka at Pages Ford is derived using the pdist command of the TIDEDA programme, then is manipulated to produce net precipitation. An appropriate proportion of annual evapotranspiration is added to the net precipitation to estimate the total precipitation. The annual evapotranspiration is estimated at 700 mmyr^{-1}; the proportion of this incorporated in calculations will depend on the length of the data period.

The generated total precipitation figures for Rameka are used, along with rainfall means from Harwoods, Kotinga, Waingaro, Canaan, Takaka Hill, Little Devil, and Caesars recorders, to construct isohyetal plots over the specified time periods. The average areal rainfall over the Central Takaka Valley subcatchment is calculated for each time period using the standard isohyetal method. Comparison of these averages with the original average net rainfall for the Rameka site enables an appropriate weighting figure to be derived. Weighting figures are then applied to respective flow inputs at Rameka. These generate a total flow contribution over the 203 km^2 of the Central Takaka Valley subcatchment for time periods A -D. Raw flow data, and data processing are presented in Appendix I.

The mean flows for the Waitui subcatchment are generated using flow data from the south branch of the Riwaka River (N26 034172). This section of the Riwaka Catchment is similar to the Waitui in its karstic nature, and is assumed to provide representative inflow figures which are more appropriate than the Rameka (pers. comm. Doyle 1997).

Indeed, if data was extrapolated from the Rameka, it would be likely to produce greater that expected flow figures. Respective areas for the Riwaka Catchment and the Waitui subcatchment are 46.2 km^2 and 38 km^2.

The figures for all data sets and all input and output components are presented in Tables 6.5 and 6.6. They represent mean flows (l/s) over the specified periods of time (A -D).

Table 6.5. Inputs of water balance data for the Waikoropupu Arthur Marble Aquifer using flow water method.

DATA SET	UPPER TAKAKA	WAINGARO	CENTRAL and WAITUI
A	17980	22983	19507
B	19422	22276	19168
C	15793	21443	13588
D	6982	9977	7138

Table 6.6. Ouputs of water balance data for the Waikoropupu Arthur Marble Aquifer using flow water method.

DATA SET	KOTINGA	PUPU
A	45929	14321
B	46277	14883
C	37357	14089
D	12659	11138

6.3.4.2 Flow water balance calculations

The calculation for data set A is given below.

Following equation 6.1, $\Delta S = Q_I - Q_D$

$$= (Q_H + Q_W + Q_{C+R}) - (Q_K + Q_P)$$

$$= (17980 + 22983 + 19507) - (45929 + 14321)$$

$$\underline{\Delta S = 220 \text{ l/s}}$$

The full results for all the data sets are presented in Table 6.7. Total error is estimated to be of the order of 15-25 %.

Table 6.7. Summary input, output, and change in storage for the four data sets (A-D) using the flow water balance. All figures are quoted in l/s.

DATA SET	INPUTS (l/s)	OUTPUTS (l/s)	ΔS (l/s)
A	60470	60250	220
B	60866	61160	-294
C	50824	51464	-640
D	24097	23797	300

The results of the flow water balance (Table 6.7) indicate that the WAM Aquifer system is relatively balanced. The average change in storage for the data sets A-D is 104 l/s. All the values for ΔS are able to be considered hydrologically insignificant for water balance purposes.

The results of this method agree with those of method one; neither method supports the existence of an 8-9 m^3s^{-1} submarine spring system (Mueller 1992). The combined results of both methods suggest that the WAM Aquifer fluctuates from a small storage deficit to a small storage surplus. The order of magnitude of Mueller's (1992) assumed springs seems to be very unlikely.

6.4 THE COBB POWER STATION

The Cobb Dam was designed and built specifically for hydroelectric purposes. The dam height measures 32.7 m, the capacity of the reservoir is 28 000 000 m^3, and the spillway capacity is 950 m^3s^{-1} (Freestone 1992, N.Z. Society of Large Dams 1989). The maximum hydroelectric power production is 32 MW.

The reservoir receives water from a total catchment area of 119 km^2, with the Cobb River being the major tributary. Other important inputs are derived from Lake Sylvester and Little Lake Sylvester. The scheme impounds the Cobb River at the reservoir, only releasing directly downstream of the dam via the spillway structure. A natural component of Cobb River flow is derived from a 40 km^2 catchment area between the dam structure and the downstream power station. Additional flow inputs are produced from machine generation discharges from the power station itself. Water used in generation is piped via a 2.6 km tunnel connecting the outlet to the twin penstocks which descend the side of the Takaka River Valley. The gross head difference between the reservoir and the power house is 594 m. The Cobb River-Takaka River confluence is approximately 200 m downstream of the machine discharge.

Generation details for 1995, 1996, and part of 1997 are given in Table 6.8. The Cobb power station ceased generating only for 21 days, in 1996. At all other times machine discharge ranges from 1140-7262 l/s.

Table 6.8. Summary details of mean monthly machine discharge for Cobb power station (in l/s).

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1995	2938	3548	6316	3957	6991	7056	7139	6824	6384	7129	5207	2148
1996	2445	4554	3341	4746	7164	4185	5278	7262	7210	6956	6313	7200
1997	5878	3359	1140	3400	3956	2799	3875	3782	na	na	na	na

na = data not available at the time of writing

6.4.1 Hydrological effects of dams, reservoirs and impounded rivers

Dams and associated reservoirs have significantly altered the hydrological regimes of many New Zealand rivers by impounding all or part of river flow for the purposes of hydroelectric generation, supply, or water conservation (Freestone 1992). Whether this impoundment involves a large river or a small stream, the downstream discharge will be changed.

Petts (1984) recognised five principal hydrological effects common to all impounded rivers. They are a reduced average annual runoff, a reduced seasonal flow variability, an altered timing of extremes, reduced flood magnitudes, and the imposition of unnatural pulses. While Petts cites many examples from major dam structures (such as the Colorado dams in the U.S.A.) he notes that actual hydrological effects occur according to the magnitude of impact. This in turn is a function of the design and operation of the dam. In the Cobb-Takaka situation the impounded Cobb River is an important tributary for the main river in the catchment, namely the Takaka River.

6.4.2 Methodology adopted

The aim of this section is to investigate the quantitative downstream hydrological effects of the Cobb power station. The methodology employed, the analysis techniques, and the presentation of results are intended to provide baseline information; they are neither exhaustive nor necessarily complete. The biological effects of the Cobb operation was the focus for a recent Masters thesis by Brown (1998), and should be consulted with regard to instream fauna and water quality effects.

Discussion on the hydrological effects of the Cobb power station is divided into three sections. They are as follows:

1. Quantification of hydrograph modification: the existing database is used to assess the effects of the generation releases on the Upper Takaka River (at Harwoods), and on Waikoropupu Springs (primary discharge zone of WAM).

2. Evaluation of flow variability: a generated data set is used to evaluate annual and seasonal effects, and to assess the impact of low flows on the Takaka River downstream of Cobb.

3. Assessment of the effects on aquifer recharge: the effects of the Cobb power station on the recharge system of WAM are evaluated, through a comparison of natural vs. measured contributions via the Takaka River sinks.

Analysis of high flows and flood events is not attempted, as only low flows are of particular interest. The timing of flood extremes is obviously altered under the present regime, and flood magnitudes would be greater under natural unmodified conditions. The Cobb reservoir acts to absorb flood peaks from the Cobb Catchment.

6.4.3 Quantification of hydrograph modification

6.4.3.1 Upper Takaka River-Harwoods recorder

The most obvious effect of the Cobb system on the Takaka River flows is the imposition of unnatural pulses. Power generation can vary from nil to maximum (32 MW), corresponding to machine discharge from 0 l/s to 7200 l/s. The timing and magnitude of both power generation and discharge releases is erratic, being dictated by the national power grid. The duration of releases is also variable.

The upper Takaka River recorder at Harwoods clearly displays the pulses in discharge records. Figures 6.1a, 6.1b display the discharge record of the Takaka River at Harwoods over selected time periods and under different flow regimes, i.e. low, moderate, and high flows. The Cobb releases are clearly seen in the record as tooth-blocks of increased discharge. Equally obvious are the periods when Cobb generation has decreased (Figure 6.1b). The river distance between the Cobb River-Takaka River confluence and the Harwoods recorder is approximately 10 km.

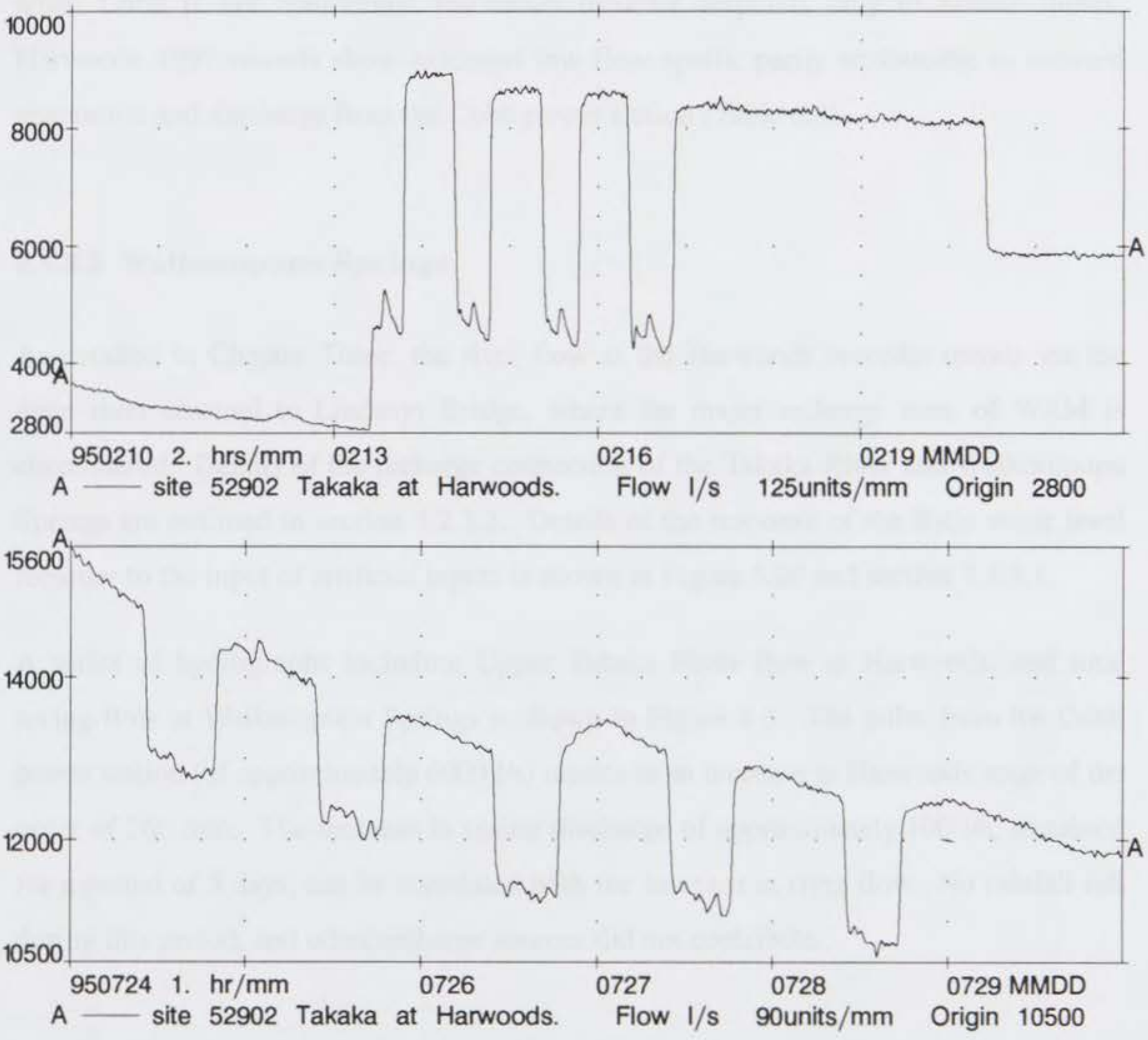


Figure 6.1 Hydrograph modification of the Harwoods flow record.

Low flow summer conditions in the Upper Takaka River are typically of the order of 1-2 m^3s^{-1}. Under these conditions, a maximum generation pulse of approximately $7m^3s^{-1}$ raises the stage at Harwoods approximately 335 mm, and accounts for a 300 % increase in flow at this site (Figure 6.2). Under prolonged generation conditions the upper Takaka River flow is greatly increased. It is common for the power station to generate at a low level; in the last 3 years the power station ceased generating completely on 21 days. Effects on the flow at Harwoods are reduced under minimal release conditions; when Cobb is not operational Harwoods recorder responds only to natural inputs. Harwoods 1997 records show extended low flow spells, partly attributable to reduced generation and discharge from the Cobb power station (Table 6.8).

6.4.3.2 Waikoropupu Springs

As detailed in Chapter Three, the river flow at the Harwoods recorder travels via the open river channel to Lindsays Bridge, where the major recharge zone of WAM is encountered. Details of the recharge connection of the Takaka River and Waikoropupu Springs are outlined in section 3.2.3.1. Details of the response of the Balls water level recorder to the input of artificial inputs is shown in Figure 3.29 and section 3.4.4.1.

A series of hydrographs including Upper Takaka River flow at Harwoods, and total spring flow at Waikoropupu Springs is shown in Figure 6.3. The pulse from the Cobb power station (of approximately 6000 l/s) results in an increase in Harwoods stage of the order of 260 mm. The increase in spring discharge of approximately 100 l/s, sustained for a period of 5 days, can be correlated with the increase in river flow. No rainfall fell during this period, and other recharge sources did not contribute.

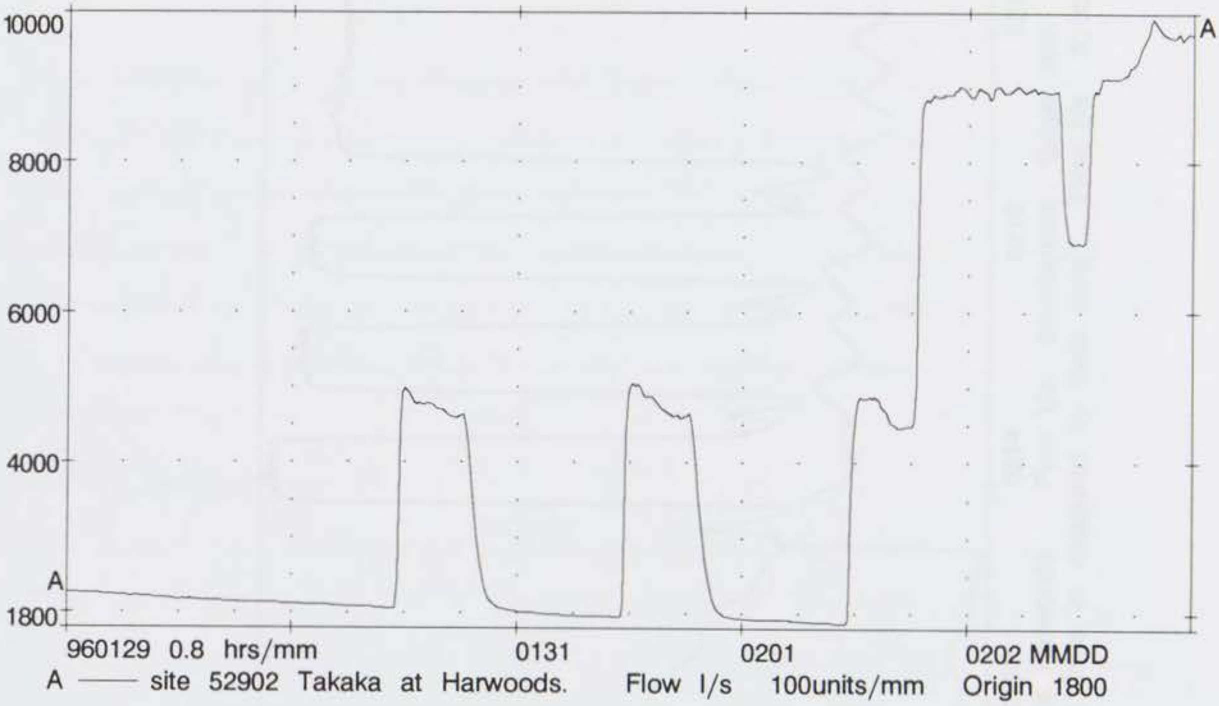


Figure 6.2.Quantification of hydrograph modification of the Harwoods flow record.

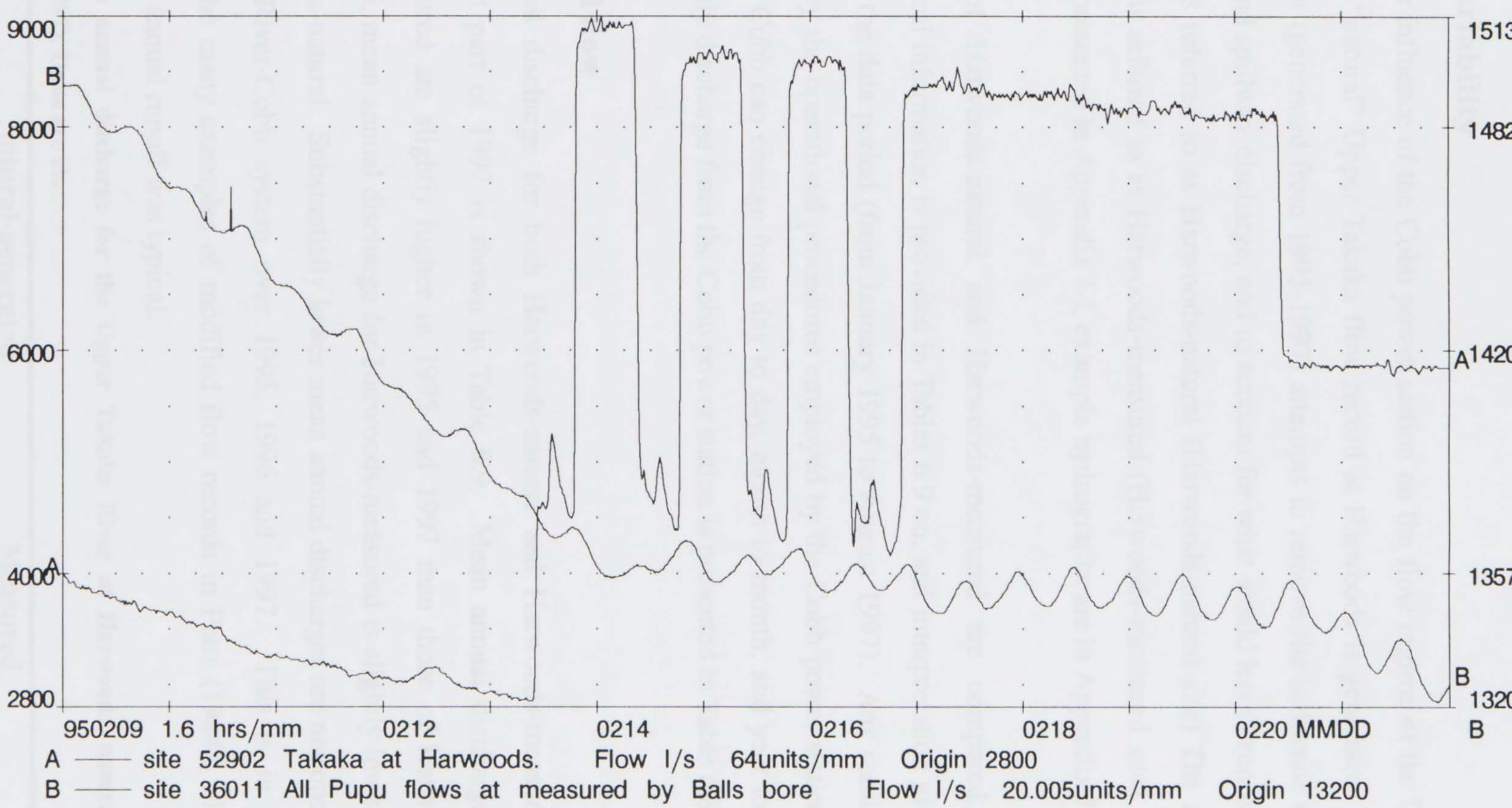


Figure 6.3. Quantification of hydrograph modification of the Pupu Springs flow record.

6.4.4 Flow variability

To determine the influence of the Cobb power station on the flow regime of the Upper Takaka River, a "natural" Upper Takaka flow record at Harwoods is generated. This modified data set (generated from 1995-1997) attempts to remove the influence of the Cobb machine and spillway discharge, and to account for what would have been natural input. Its flow is referred to as Harwoods-natural (Harwoods-natural site) The actual Harwoods flow is referred to as Harwoods-measured (Harwoods-measured site) Data manipulation is presented in Appendix J-I, example hydrographs are in Appendix J-II.

Flow records of Harwoods-natural and Harwoods-measured are compared. The summary statistical information is provided in Tables 6.9 on, and interpretation given is only relevant to the data period (from January 1995 to August 1997). Any results are totally dictated by the operational procedures employed by the Cobb power station; the discharges from Cobb can change from day to day, month to month, and year to year. The mean monthly discharge from the Cobb power station is presented in Table 6.8.

6.4.4.1 Annual flow

The mean annual discharge for both Harwoods-natural and Harwoods-measured in 1995, 1996, and part of 1997 is shown in Table 6.9. Mean annual discharges for Harwoods-measured are slightly higher in 1995 and 1997 than those of Harwoods-natural. In 1996, mean annual discharge for Harwoods-measured is slightly lower than that of Harwoods-natural. Substantially lower mean annual discharges are not observed in the Takaka River-Cobb system over 1995, 1996 and 1997. This is in direct comparison to the many examples of modified flow records in Petts (1984), where a reduced average annual runoff was typical.

Table 6.9. Mean annual discharge for the Upper Takaka River at Harwoods, natural and measured (1995-1997). Units are l/s.

	Natural-generated	Measured
1995	18611	19204
1996	16316	16224
1997*	7734	7805

*for the months Jan-Sept only: a full dataset from ECNZ-Cobb was not made available

6.4.4.2 Seasonal variability

Mean monthly flows are computed for Harwoods-natural and Harwoods-measured to determine if there are any obvious differences in seasonal patterns of flow. While the 3 year data set is too short to give a good long term representative pattern (a 20-30 year data set would be needed), a comparison of mean monthly flows is still considered useful. A plot of variation in mean monthly flows from 1995 to August 1997 is shown in Figure 6.4. Mean monthly discharge details are presented in Appendix J-III.

Figure 6.4 shows a similar seasonal pattern of flow for the Harwoods-natural and Harwoods-measured records. Increased mean monthly discharge are typically recorded in July to October, followed by low periods of flow between December and March. The Harwoods-natural record shows a more pronounced response to higher summer mean monthly flow (attributable to summer storms). For 13 out of the 32 months plotted the estimated mean monthly flows at Harwoods-natural are higher than those of Harwoods-measured. During 1995, higher mean monthly flows are generated for Harwoods-natural in the months of February, April, August, and December. During 1996, the mean monthly flows for the measured site and the natural-generated site are relatively similar (March, April, June, July, September, October, and November all have higher natural-generated means). The mean monthly flows for December 1996 to July 1997 for both natural and measured sites are given in Table 6.10. The difference represents an estimate of the deficit or surplus between the measured and generated flow means. A positive value indicates that the present regime discharged more water than would have flowed under natural conditions, and vice versa. Hydrographs for January and February are shown in Figure 6.5.

Table6.10. Summary statistics for December 1996-July 1997 for measured and generated natural flow at the Harwoods recorder.

	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul
Harwoods (measured)	10040	9430	7280	3100	7380	7040	10920	5830
Harwoods (natural)	5990	5700	5950	3500	9000	5840	13020	4510
Difference	+4050	+3730	+1330	–400	−1620	+1200	−2100	+1320

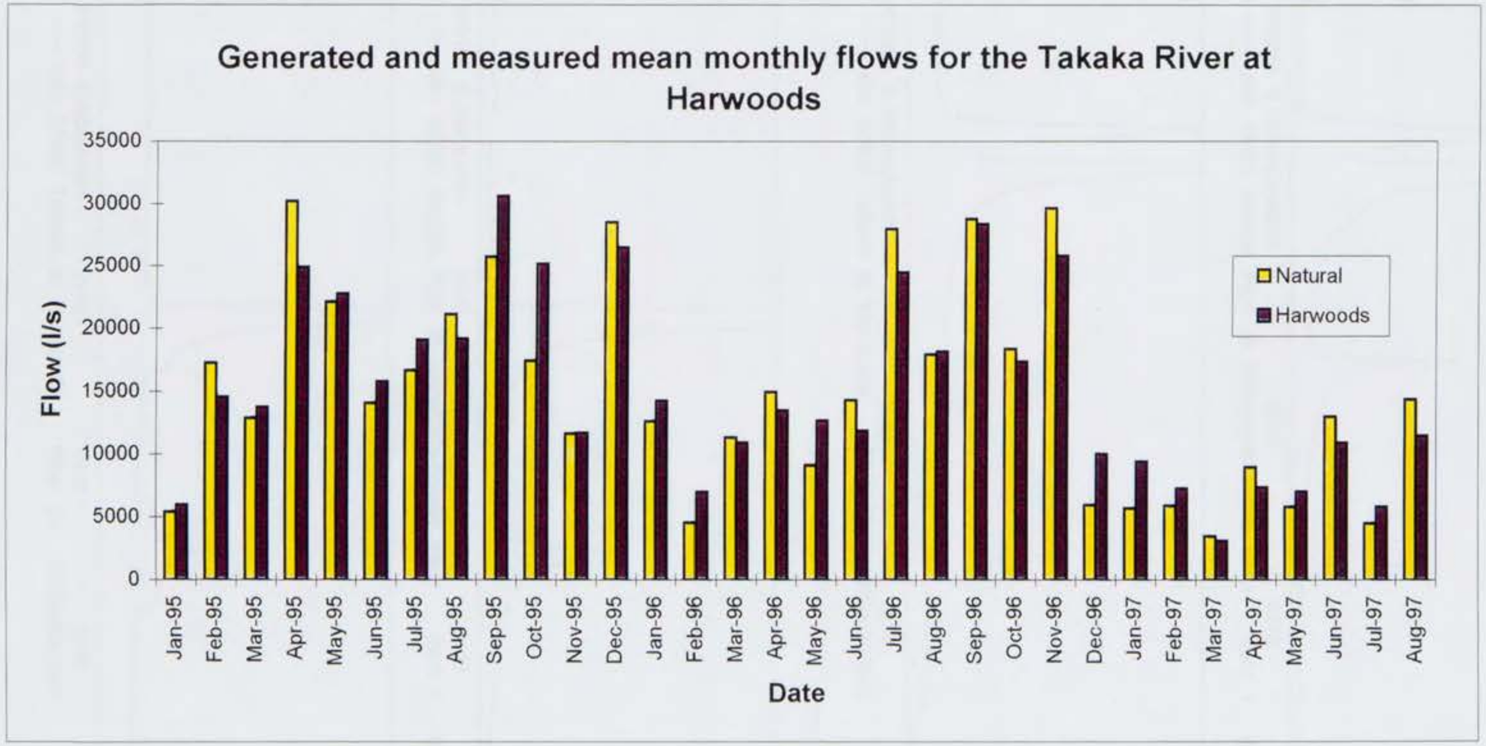


Figure 6.4. Comparison of mean monthly flows for natural-generated Harwoods flow and measured Harwoods flow

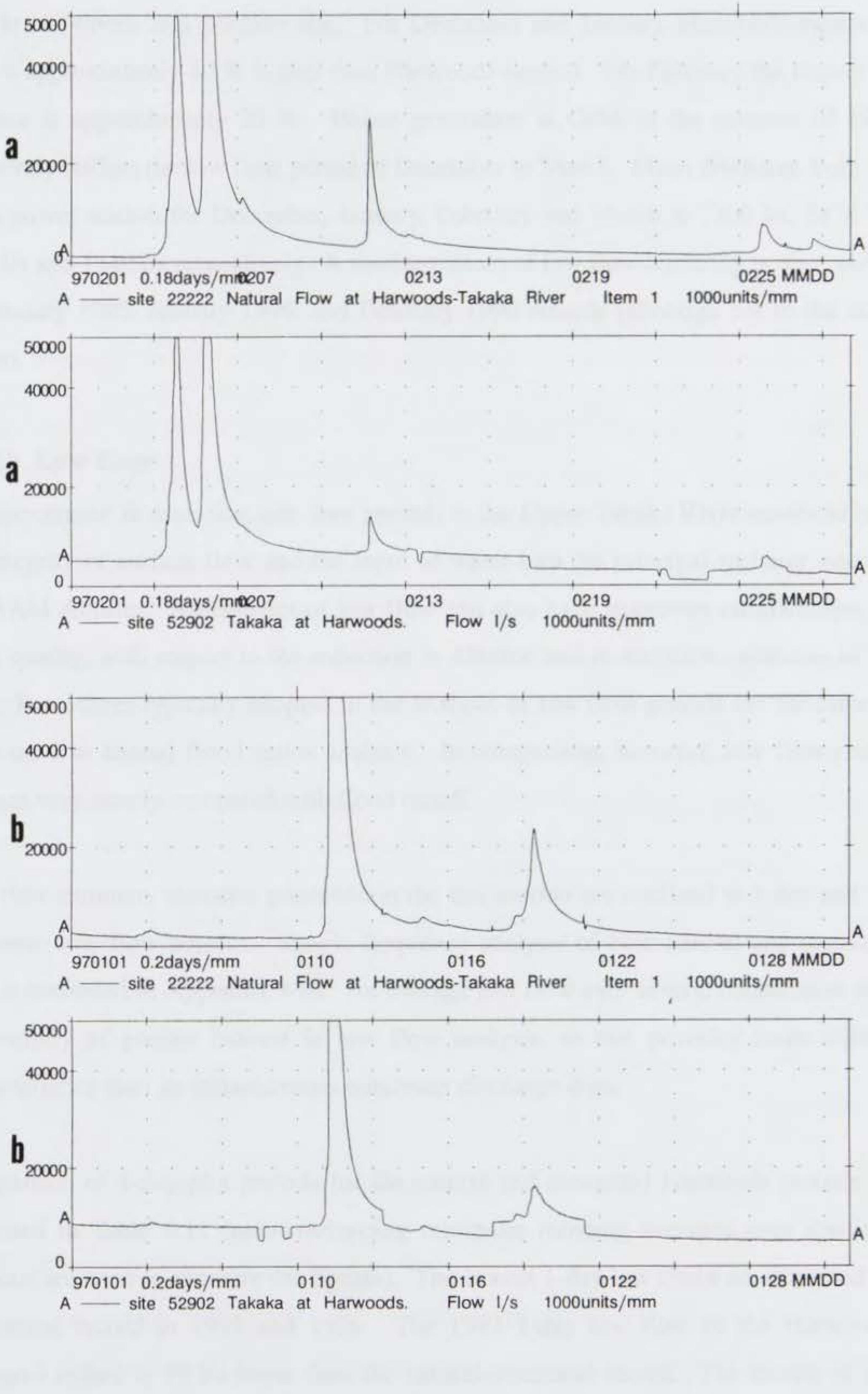


Figure 6.5. Example hydrographs of Harwoods-natural flow and Harwoods-measured flow.

For the 1997 record the influence of Cobb generation releases on Upper Takaka River flow at Harwoods is a positive one. For December and January, Harwoods-measured flow is approximately 40 % higher than Harwoods-natural. For February the respective increase is approximately 20 %. Hence generation at Cobb in the summer of 1997 effectively buffers the low flow period of December to March. Mean discharge from the Cobb power station for December, January, February and March is 7200 l/s, 5878 l/s, 3359 l/s and 1140 l/s respectively. A similar pattern of low flow buffering is observed in the January 1995, January 1996, and February 1996 records (although not to the same extent).

6.4.4.3 Low flow

The importance in assessing low flow periods in the Upper Takaka River relates to both the integrity of surface flow and the input of water into the principal recharge zone of the WAM Aquifer. Assessment of low flow can also have important ramifications for water quality, with respect to the reduction in dilution and re-areration capacities of the river. Procedures typically adopted in the analysis of low flow periods are the same as those used in annual flood series analysis. In comparison, however, low flow runoff changes very slowly compared with flood runoff.

Low flow summary statistics presented in the this section are confined to 1-day and 10-day mean low flow periods. Simple frequency analysis of both natural and measured flow is presented in Appendix J-III. An average low flow over several consecutive days is generally of greater interest in low flow analysis, as this provides more reliable characteristics than an instantaneous minimum discharge does.

Comparison of 1-day plot periods for the natural and measured Harwoods records are presented in Table 6.11 (non-overlapping minimum movimg averages over specified intervals are used to estimate the figures). The lowest 1-day low flows are observed for the natural record in 1995 and 1996. The 1997 1-day low flow of the Harwoods-measured record is 59 l/s lower than the natural-generated record. The timing of low flow means is concordant in 1995, and differs in 1996 and 1997.

Table 6.11. Annual minimum 1-day low flow means for the Takaka River at Harwoods (natural-generated and measured. Date time format is yymmdd hhmmss.

Interval	Natural-generated	Measured
1995	1158 l/s	1760 l/s
	950121 114500	950121 80000
1996	1706 l/s	1739 l/s
	960301 103000	960211 3000
1997	1153 l/s	1094
	970202 160000	970222 201500

The annual 10-day minimum daily flow is the average of the ten lowest consecutive daily mean discharges (using non overlapping minimum moving averages over specified time intervals). Table 6.12 gives the natural-generated and measured results for 1995, 1996, and 1997. Lower 10-day means are observed in the natural-generated record for all three years. The respective differences are 572 l/s, 32 l/s, and 453 l/s. The timing of 10-day low flow events is not concordant for either annual period, although in 1995 both 10 day periods started in January.

Table 6.12. Annual minimum 10 day low flow means for the Takaka River at Harwoods (natural-generated and measured). Start time is given in yymmdd hhmmss format.

Interval	Natural-generated	Measured
1995	1415 l/s	1987 l/s
	950116 81012	950113 161500
1996	2722 l/s	2754 l/s
	960221 150000	960324 150000
1997	1523 l/s	1976 l/s
	970125 4000	970311 204500

6.4.5 Effects on the downstream river

It has been claimed (Rodney 1993), and is suspected (by the Department of Conservation) that the Cobb power scheme exacerbates the drying of the section of Takaka River overlying the primary recharge reach of the WAM Aquifer. As discussed in previously (3.2.3.1, A-D) this reach (between Lindsays Bridge and upstream of Spring Brook) typically runs dry for about 100 days a year. As well as impacting on water resources and water supply, this has important biological implications. For example, a dry river stretch can act as a natural barrier to fish migration. A comparison of the occurrences of dry river stretches under natural-generated flow and Harwoods measured - flow is therefore of interest.

A comparison of mean daily discharges of Harwoods-natural and Harwoods-measured records for 1995, 1996, and part of 1997 is made. This comparison is based on two assumptions, namely that the maximum sink capacity of the Takaka River recharge sinks is approximately 10000 l/s, and that Takaka River flow at Harwoods less than 10000 l/s results in the drying of the recharge reach, at least in part. These assumptions are presented in Section 3.2.3.1 D. Daily mean flow values of less than 10000 l/s are therefore assumed to represent drying of the recharge reach (at least in part). Results are given in Table 6.13.

Table 6.13. Comparison of estimated dry river days in the Takaka River recharge reach for natural and modified flow regimes.

	Harwoods-natural	Harwoods-measured
1995	150	107
1996	209	128
1997*	196	206

* Records are only available for January-August. Data gaps of 29 days and 6 days occur in the Harwoods-natural record for 1995 and 1996 respectively.

Clearly all results are governed by the generation conditions adopted by Cobb in 1995, 1996 and 1997. The releases associated with the Cobb power station (and ultimately the regulation of Harwoods flow) result in less dry river days (at least in part) compared with the number predicted in the natural-generated record. In the partial record of 1997 (up till the end of August) the number of dry river days are comparable. Hydrograph records for 1997 (both natural-generated and measured) are characterised by extended dry spells. River flow in 1997 is therefore typically under 10000 l/s, even with Cobb releases.

6.4.6 Effects on aquifer recharge

A study of the effects of the Cobb power station on the recharge system of WAM (and ultimately on Waikoropupu Springs discharge) is a logical progression from the study of comparisons of Harwoods-natural and Harwoods-measured flow and how these effect the drying of the Takaka River (downstream of Lindsays Bridge) (section 6.4.5). It is proposed that under specific generation regimes the Cobb power station has the potential to enhance the recharge of the WAM Aquifer. The reservoir has the ability to store major flood peaks and the power station can then discharge during periods of lower river flow. At such times the aquifer would be more receptive to recharge.

Methods of analysis adopted in this section parallel those performed in section 3.2.3.1.C for the quantification of the Takaka River sink contribution. Similar assumptions on sink capacity, water table behaviour, and recharge style are also adopted. The natural-generated flow record at Harwoods is manipulated, in order that all flow under the 10000 l/s sink capacity threshold can be assumed to contribute to WAM recharge. Generation of this natural recharge site allows summary statistics (such as mean monthly flows and mean annual flows) to be derived with ease. Table 6.14 presents the mean annual recharge contribution for 1995, 1996, and part of. 1997.

Table 6.14. Comparison of estimated mean annual recharge contributions from natural-generated and measured Harwoods flow for 1995, 1996, and 1997. Units are m^3s^{-1}.

	Natural river contribution	Harwoods measured contribution
1995	$242 \times 100\,000$ m^3s-1	$276 \times 100\,000$ m^3s-1
1996	$229 \times 100\,000$ m^3s-1	$237 \times 100\,000$ m^3s-1
1997*	$142 \times 100\,000$ m^3s-1	$185 \times 100\,000$ m^3s-1

* Only calculated from January-August.

Figure 6.6 presents the mean monthly recharge contribution into the WAM Aquifer via the Takaka River sinks for both natural flow and measured (or modified) flow.

MEAN MONTHLY RECHARGE CONTRIBUTION UNDER NATURAL FLOW CONDITIONS (generated Harwoods)												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1995	2699	5646	6847	8702	8390	8489	9532	9212	9987	9021	7670	6182
1996	5711	3840	6096	7800	6177	8081	8714	8876	9259	8661	8894	5127
1997	3468	3751	2998	4891	4419	5648	3622	7196	na	na	na	na
MEAN MONTHLY RECHARGE CONTRIBUTION UNDER MODIFIED FLOW CONDITIONS (measured Harwoods)												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1995	4410	7210	9510	8950	9890	9980	10000	9970	9880	10000	8840	6510
1996	6550	6700	7010	8790	9680	8640	9510	10000	10000	9990	9850	9290
1997	7450	5410	2930	5750	6110	6080	5560	7940	nc	nc	nc	nc

na= not available, nc= not calculated

Table 6.15. Estimated mean monthly recharge contribution from Harwoods-natural and Harwoods measured

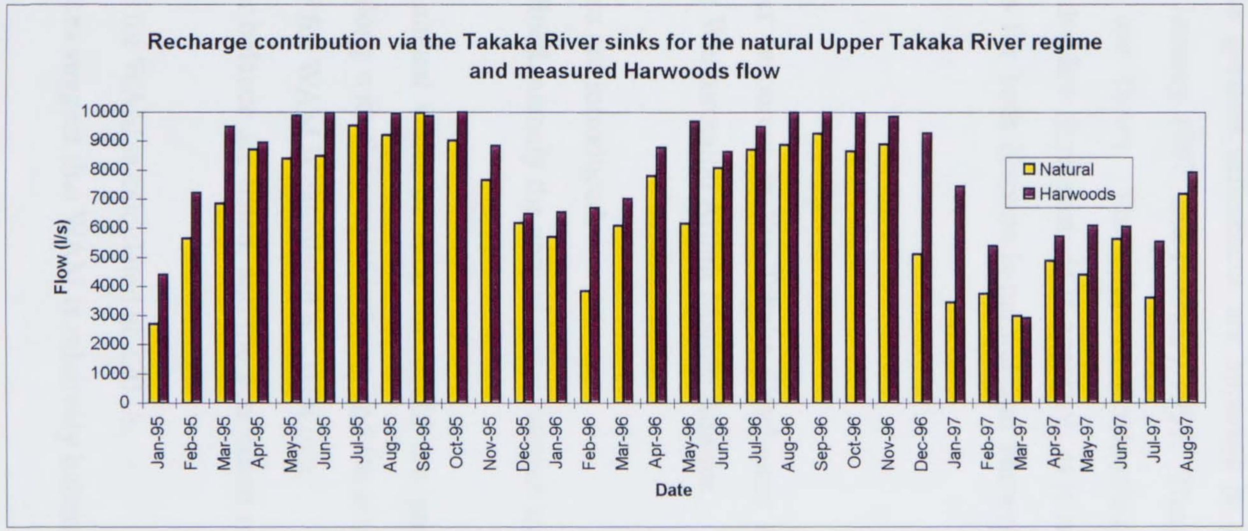


Figure 6.6. Histogram of mean monthly recharge contribution from Harwoods-natural and Harwoods measured

Both recharge records display a distinct seasonal input. Higher recharge is observed from June to October, followed by lows from December to March. For all months (with the exceptional of March 1997) the Harwoods-natural recharge contribution is less than that of Harwoods-measured. Mean monthly recharge contributions for Harwoods-natural and Harwoods-measured are given in Table 6.15. Harwoods-measured figures are represented from Table 3.3. The greatest differences are apparent in January 1995, February 1996, December 1997, January 1997, and February 1997. These all coincide with summer periods of typical low flows. The effect of Cobb releases on WAM recharge during extreme or extended low flow periods is apparent, as it is with the low flow and mean monthly statistics for both Harwoods-natural and Harwoods-measured sites.

6.5 SYNTHESIS

Two specific evaluations of water resources in the Takaka Catchment are presented. The first is a water balance for the Waikoropupu Arthur Marble Aquifer.

- General water balance principles are introduced.
- Two alternate methods are outlined, namely the annual water balance method and the flow balance method.
- Input and output data for an annual water balance for WAM are presented. The precipitation input is derived, along with the sum of inflows, and the total outflow.
- The resulting change in storage for WAM is calculated at - 0.44 m^3s^{-1}.
- Components for the flow water balance are listed, and the generation of mean flows using TIDEDA is outlined.
- The resulting change in storage for WAM is calculated at 220 l/s.
- The results of both water balances suggest that WAM is relatively balanced.

The second feature looked at is the Cobb hydroelectric scheme A preliminary assessment of the hydrological effects of Cobb on the downstream Takaka River and the Waikoropupu Arthur Marble Aquifer is presented.

- The effects that Cobb has on the hydrology downstream are totally determined by the generation regimes employed by the power station.
- A modified or generated data set quantifies Cobb's influence on the flow regime of the Upper Takaka River.
- The variability of annual flow and seasonal flow is discussed. Little variation in mean annual flow is predicted, and seasonal flow is totally dependent on the power station.
- Data set manipulation provides an estimate for the recharge system of WAM.
- Cobb's influence on the Upper Takaka River is most obvious under low flows. The generation regime does not necessarily exacerbate the drying of the Takaka River.
- Cobb's generation regime can advantage WAM in low flow periods.
- For the 1995 to 1997 data, measured input into the recharge system of WAM is higher than predicted for the Harwoods-natural site.

CHAPTER SEVEN : SUMMARY AND CONCLUSIONS

7.1 PROJECT BRIEF

This thesis aims to review all available information and utilise the extensive database available for the Takaka Catchment. It integrates all existing data, information, and research for the area, and is intended to provide information for the Takaka Water Management Plan. The investigations involve field work, database analysis, and aquifer systems analysis, which is developed from a broad hydrogeological base covering diverse aspects of geology, hydrogeology, water chemistry, and water resource management.

This chapter is divided into five further sections; each focuses on one of the karst and gravel aquifers studied. The intention is to highlight the individual significance of each aquifer by integrating all pertinent information. The final section presents principal conclusions and recommendations for management.

7.2 THE WAIKOROPUPU ARTHUR MARBLE AQUIFER

The Waikoropupu Arthur Marble Aquifer is the major karst aquifer in the Takaka Catchment. It is comprised of two sections, namely a confined section measured from north of Gorge Creek to Waikoropupu Springs, and an unconfined section south of Hamama. The extent and distribution of the confining Motupipi Coal Measures determine the nature of the aquifer boundaries.

The recharge system of WAM is complex, and is comprised of a number of components, both allogenic and autogenic. The contributing areas cover the entire Takaka Catchment. The recharge system is dominated by the Takaka river sinks, which are estimated to contribute some 55% to total recharge. The study of the Takaka river sink contribution is based on examination of the existing gauging database, and a number of assumptions have had to be made due to the lack of hydrogeologic and hydraulic controls. The behaviour of the aquifer underlying the Takaka River is that typical of a mixed karst-alluvial system, with gradual seepage dominating over specific point loss. The Waingaro river sinks and tributary stream sinks contribute between 20% and 30% of WAM recharge, and diffuse recharge inputs (both allogenic and autogenic) provide the remaining recharge. The contribution from the Anatoki River is assumed to be negligible.

The primary discharge site of WAM is the Waikoropupu Springs system. These comprise of two principal subsystems, namely Pupu Springs (comprised of Main Springs and Dancing Sands) and Fish Creek Springs. The hydraulic connections between the subsystems are not simple, but they can be envisaged as a vertical hierarchical system. This does not, however, imply that Fish Creek Springs is a simple overflow spring.

The existence of an 8-9 m^3s^{-1} submarine spring discharging from WAM is refuted. There is no geological, physical, or water chemistry evidence to support this discharge. A water balance performed in the WAM Aquifer provides further evidence for the non-existence of the submarine springs. The water balance, using two methods, shows that the aquifer system is relatively balanced, with both excess and deficit of the order of 1-2 m^3s^{-1}. This is within error, and considerably different in magnitude to the claimed submarine discharge figure.

An extensive temporal water quality database for the discharge of WAM exists at the Pupu Springs site. The water chemistry of data from this site reflects its situation near the coast. The ionic chemistry is variable, changeable, and complex. Elevated levels of chloride, sodium, potassium, and magnesium are all attributed to input from sea water, but this does not necessarily imply the need for a direct connection between WAM and the sea. Water chemistry findings do not necessarily support the existence of submarine springs.

Waikoropupu Springs discharge fluctuates in response to short term effects (resulting from both natural and artificial inputs), and to tidal fluctuations. The part of WAM near Waikoropupu Springs fluctuates similarly. There is no clear relationship between the springs system and Balls water level recorder. Balls taps the karst conduit, which does not have a simple hydraulic connection to the springs, as previously assumed. This provides evidence of a hydrogeologic arrangement which is more complex than previously thought.

Because of its relationship to Waikoropupu Springs, management of the WAM Aquifer is critical. The most obvious human influence is in the effect of generation releases associated with the Cobb power station. These affect the hydrographs of Waikoropupu Springs, alter the Upper Takaka River regime, and modify recharge input into the Waikoropupu Arthur Marble Aquifer. Influences on river flow are particularly apparent during low flow periods. The Upper Takaka River regime regulates the input available to the aquifer recharge reach, and under low flows (less than 10000 l/s) all river water is expected to contribute.

Generation practices employed in 1995-1997 did not exacerbate the drying of the recharge reach. In fact, Cobb had a positive effect on recharge input, as shown by the assessment of generated recharge records. The reservoir was able to store flood peaks which would otherwise have been released to the sea, and release flow during drier periods when river conditions were low and WAM was receptive to recharge.

7.3 THE EAST TAKAKA-MOTUPIPI LIMESTONE AQUIFER (ETML)

The East Takaka-Motupipi Limestone Aquifer is the minor karst aquifer in the Takaka Catchment. It is confined to the underlying WAM by the Motupipi Coal Measures, and confined to the overlying gravels by the Tarakohe Mudstone. ETML is situated in the north-eastern part of the Takaka Catchment. Its structural complexity requires it to be subdivided into three sub-aquifers, namely the East Takaka, Central Takaka-Motupipi, and Clifton sub-aquifers. The delineation of these sub-aquifers and the assessment of their hydraulic and hydrogeologic isolation are both critical for management purposes. ETML is an important source of domestic and agricultural water; usage is likely to increase with further demands and developments. The alternative water sources for the area, shallow gravel and surface water, are unreliable.

The recharge of ETML is mixed, comprised of diffuse autogenic and allogenic rainfall as well as concentrated allogenic recharge from the Takaka River and the Dry River stream sinks. Discharge sites are at East Takaka Springs and Motupipi Springs. No information is available on the discharge component, and no water balance can therefore be conducted.

The aquifer fluctuates in response to short term and seasonal effects, and no long term trend is apparent. The type of fluctuation, and the order of magnitude, differs between the sub-aquifers, according to the location of each relative to the recharge source. The East Takaka sub-aquifer responds to the Takaka River, while tidal fluctuations are seen in the Central Takaka-Motupipi sub-aquifer.

An extensive temporal water chemistry database is available for one bore only (WWD 6601), which is located in the Central Takaka area. The water chemistry of ETML typifies that of karst limestone aquifers. Variations are not of the same extent as those of Pupu Springs. Samples of ETML groundwater comply with NZDWS, but the aquifer is prone to water contamination due to its karstic nature. Preservation of water quality is of utmost importance if the water resource is going to be further utilised.

7.4. TAKAKA TOWNSHIP GRAVEL AQUIFER (TTG)

The Takaka Township Gravel Aquifer is the primary water source for the Takaka Township. It is part of the extensive Quaternary deposits which floor the Takaka Valley, and is comprised of a 10-20 m thin layer of Holocene river alluvium. The spatial delineation of TTG adopted in this thesis has been devised primarily for management purposes and does not necessarily coincide with any hydrogeological divides.

The primary recharge sources for TTG are the Lower Takaka River (the major contributor), diffuse input, and inputs from the Motupipi River. The assessment of gauging runs performed in this thesis supports these conclusions. Little further gauging information is available, and as a result mean river recharge contribution is not able to be quantified. A number of discharge sites are identified, predominantly proximal to the Takaka River. The major gravel springs discharge is at Tekakau, which is a reemergence of the river. Other springs are located near the coast at Waitapu, and act as overflow seeps to TTG.

Flow in the central section of TTG is to the north, while in the Motupipi section is to the northwest. The divide between the two flow sections is where Takaka Limestone crops out at Birch Hill. The average hydraulic gradient for the three water level surveys conducted is 1.75 m/km. The fluctuations observed between the summer surveys (January, and March, 1998) and the winter survey (August 1998) are of the order of 1 m.

The results of the TTG groundwater quality survey of 1996 comply with NZDWS. Comparison of nitrate levels between 1986 and 1996 surveys is made difficult by the lack of consistent sites. Levels above the mean are typically recorded in farming areas, but all levels are below those stated in NZDWS.

A zone from east of the Takaka River at Kotinga Bridge to the Motupipi River records consistently elevated alkaline earths, nitrate levels, and conductivity levels. This area is dairy farming land, and must be monitored accordingly. Only a few samples record biological contaminants, but this renders them unsafe to drink (according to NZDWS guidelines). TTG groundwater is deemed suitable for irrigation purposes. It would be most beneficial if all the TTG wells incorporated in the 1996 survey were resampled in the next year for comparison.

7.5 THE EAST TAKAKA GRAVEL AQUIFER (ETG)

The East Takaka Gravel Aquifer represents an area of Quaternary gravels in the eastern section of the Takaka Valley, at the base of the Pikikiruna Range. The spatial delineation of ETG has been devised primarily for management purposes and does not necessarily coincide with any hydrogeological divides. The ETG Aquifer is used for agricultural purposes, and some domestic supply. Additional water in the East Takaka region comes from deeper bores which tap the ETML Aquifer, and from surface water schemes.

ETG is subdivided into two sections, which are described as the Bainham terraces and the river alluvium deposits. Primary recharge sources are diffuse inputs, together with input from the Takaka River. The latter primarily affects the river alluvium section, which responds rapidly to input events.

The groundwater flow is in a general north to northwest direction. Delineation of flow patterns across the two segments of ETG is not clear. The hydraulic gradients increase in the northern sections, where recharge derived from the high terraces dominates. Water level surveys conducted in 1997 show only slight seasonal variations (of the order of 1.5 m). The dry winter conditions of 1997 contributed to the lower than average winter water levels.

The water quality of the ETG Aquifer complies with NZDWS. Little variation in major ion constituents is observed in the 1996 groundwater quality survey. A comparison of nitrate levels between 1986 and 1996 shows slight differences. Only limited sites were available for water quality analysis, and the lack of detail of some ionic constituents precludes assessment of SAR levels. The ETG Aquifer is assumed to be suitable for irrigation purposes.

The ETG Aquifer is an unreliable water source during extended dry periods. Wells which tap the aquifer have been known to run dry. Any increased usage of the ETG Aquifer is not appropriate at the present time, and the preservation of its water quality is critical.

7.6 PRINCIPAL CONCLUSIONS

7.6.1 Existence of Submarine Springs

Submarine Springs with a magnitude of 8-9 m^3s^{-1} discharging from the WAM Aquifer do not exist. It is highly unlikely that submarine springs of any magnitude exist.

7.6.2 Waikoropupu Arthur Marble Aquifer Recharge

Recharge of the Waikoropupu Arthur Marble Aquifer is dominated by input from the Takaka river sinks. There are inadequate water quality protection measures in place, particularly of the primary recharge zone in the Takaka River.

7.6.3 Waikoropupu Arthur Marble Aquifer Discharge

The primary discharge site of the Waikoropupu Arthur Marble Aquifer, Waikoropupu Springs, is a highly complex karst spring system, with no simple conduit connections existing. The water chemistry of Waikoropupu Springs is complex, and not fully understood.

7.6.4 The East Takaka-Motupipi Limestone Aquifer

The East Takaka- Motupipi Limestone Aquifer is potentially a good water source for the Takaka Township, and the East Takaka, Central Takaka, and Motupipi areas. Further exploitation is not advised, however, until a more detailed hydrogeological assessment has been performed.

7.6.5 The Takaka Township Gravel Aquifer and the East Takaka Gravel Aquifer

The shallow gravel aquifers provide a good water supply for domestic and agricultural use. Supplies in certain areas, however, are unreliable. Both gravel aquifers are prone to water quality degradation.

7.6.6 The Influence of the Cobb Power Station

Subject to the limitations of the short term data set, the Cobb generation releases appear to have no detrimental effect on the Upper Takaka River regime. For the years 1995-1997, it does in fact increase recharge to WAM.

7.7 MANAGEMENT RECOMMENDATIONS

7.7.1 Waikoropupu Arthur Marble Aquifer

- WAM requires a monitoring bore at Waikoropupu Springs, in order to increase the robustness of spring discharge data.
- The Takaka River preferably requires three water level monitoring bores in WAM's recognised recharge zone. Recommended locations are: one directly next to the river, one which encounters both limestone and marble, and one proximal to the two fore-mentioned. There must be detailed logging of results.
- If any bores are found to encounter limestone or marble, they need to be set with piezometer nests.
- Analysis and modelling of the chemical water quality database is needed.

7.7.2 The East Takaka-Motupipi Limestone Aquifer

- A more detailed geological study of ETML is needed, involving mapping of sub-aquifer boundaries and structural mapping of folds and faults.
- The continuous measurement of a representative Central Takaka bore in the north-western fold belt would help assess the potential subdivisions of ETML.
- There must be monitoring of the spring discharge sites at East Takaka Springs and Motupipi Springs.
- The output components of ETML must be better quantified so that a water balance can be attempted.
- Further spatial water chemistry sampling is required, especially at sites near the coast where sea water contamination is possible.

7.7.3 The Gravel Aquifers

- Continuous monitoring of water levels in TTG needs to be instigated. This will require the installation of water level recorders, and a monitoring well located central to the Takaka Township would provide the most representative information. Tidal conditions will need to be taken into consideration.

- Monitoring of ETG to assess the recharge contribution from the Takaka River is recommended. More measurable and accessible wells are required.
- There must be regular implementation of water quality sampling for both aquifers.

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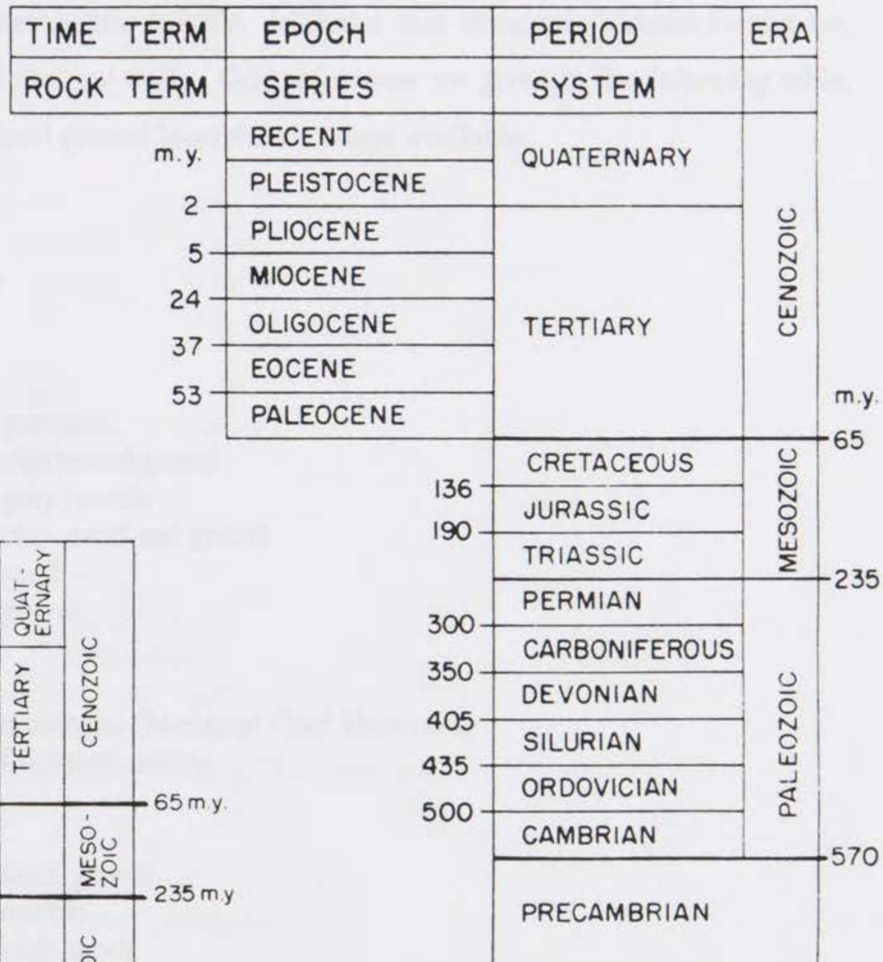
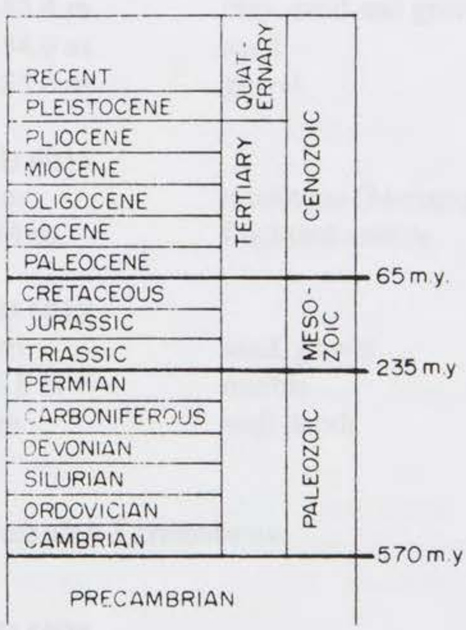
APPENDICES

APPENDIX A-I Geological time periods



THE GEOLOGIC TIME SCALE

(m.y. = million years before present)



ABBREVIATED TIME SCALE

APPENDIX A-II Borehole information

Available borehole information is presented below. Description and detail will vary. Many details were transferred from bore cards stored at Tasman District Council. Some are derived directly from drillers' logs. The information is divided into sections, namely drillholes that encounter Arthur Marble, drillholes that encounter Takaka Limestone, and Quaternary gravel shallow wells. Grid references are given in the following table, with RLGL (reduced level ground level)values where available.

1. Arthur Marble

WWD 6710

0-29 m	gravel
29-72.7 m	claybound gravel
72.7-75.8 m	grey marble
75.8-83.4 m	clay, sand and gravel
83.4-84.0 m	sand
84.0-85.0 m	gravel

WWD 6011

0-33 m	mudstone (Motupipi Coal Measures)
33-114 m	fractured marble

WWD 6815

0-12 m	sand, gravel
12-48.8 m	marble
48.8 m	well depth

2. Takaka Limestone

WWD 6808

0-8.2 m	loose gravel, coarse sand
8.2-122.5 m	Tarakohe Mudstone
122.5-125 m	Takaka Limestone

WWD 6814

0-9.1 m	gravel
9.1-44.8 m	Tarakohe Mudstone
44.8 m+	Takaka Limestone

WWD 6821

0-8.4 m	gravel
8.4-62.5 m	Tarakohe Mudstone
62.5-64.0 m	Takaka Limestone
WWD 6601	
0-33.5 m	no details given
33.5-54.6 m	Takaka Limestone
WWD 6604	
0-36.6 m	Takaka Limestone
36.6-40.0 m	broken limestone
40-42.6 m	Motupipi Coal Measures
WWD 6605	
0-6 m	gravel, claybound
6-55 m	Tarakohe Mudstone
55-85.6 m	Takaka Limestone
WWD 6610	
0-6 m	clay
6-11 m	Tarakohe Mudstone
11-44 m	Takaka Limestone
WWD 6612	
0-4 m	gravel
4-6 m	grey mudstone
6-11 m	grey limestone
11-14 m	whitish grey limestone
14-96 m	greyish limestone
99-114 m	black clay, traces of coal, Motupipi Coal Measures
WWD 6615	
0-12 m	no detail given
12m+	cavernous limestone
WWD 6405	
0-6 m	clay bound gravels
6-21.3 m	Tarakohe Mudstone
21.3-107 m	Takaka Limestone
WWD 6408	
0-18 m	clay
18-24 m	limestone
24-35 m	clay
35-61 m	broken limestone
WWD 6409	
0-5 m	clayboundgravels
5-30 m	Tarakohe Mudstone
30-32.9 m	Takaka Limestone

WWD 6410

0-5.5 m	gravel
5.5-18 m	Tarakohe Mudstone
18-24 m	Takaka Limestone
24-35 m	clay filled cavity in limestone
35-70 m	Takaka Limestone
70-71.9 m	Motupipi Coal Measures

WWD 6412

0-12.2 m	claybound gravel
12.2-20.1 m	clay
20.1-23.8 m	limestone

WWD 6413

0-4 m	claybound gravel
4-20.2 m	clay
20.2-31.4 m	limestone

WWD 6418

0-21 m	claybound gravel
21-45.7 m	broken limestone

WWD 6422

0-22.5 m	claybound gravels
22.5-42.0 m	Takaka Limestone
42-60.5 m	Motupipi Coal Measures

WWD 6423

0-15 m	clay, some stones
15-46 m	Takaka Limestone

WWD 6224

0-10 m	coarse sand and gravel
10-11.9 m	brown silty clay
11.9-13.1 m	coarse sand, gravel
19.2-24.6 m	limestone
24.6-27.1 m	clay filled cavity
27.1-28.4 m	limestone
28.4-28.9 m	clay filled cavity
28.9-48.5 m	Takaka Limestone

WWD 6109

0-12 m	gravel
12-33 m	Takaka Limestone
33-36 m	Motupipi Coal Measures, silica sand

WWD 6120

0-2.5 m	silts, sands and estuarine material
2.5-3.5 m	coarse gravels
3.5-15 m	coarse medium gravels
15-18 m	limestone

3. Quaternary Gravel wells

WWD 6811

0-0.9 m	clay soil
0.9-6.5 m	loose open gravel
6.5-7.1 m	Tarakohe Mudstone

WWD 6818

0-6.7 m	gravel, coarse sand
6.7-6.9 m	Tarakohe Mudstone

WWD 6824

0-13 m	gravels
13-14 m	mudstone

WWD 6902

0-3.6 m	gravel, loose
3.6-4.6 m	Tarakohe Mudstone

WWD 6905

0-9 m	gravel
9-45 m	Tarakohe Mudstone

WWD 6906

0-9 m	gravel
9-69 m	Tarakohe Mudstone

WWD 6703

0-11.6 m	gravel, grey
11.6 m	welldepth

WWD 6704

0-1.2 m	soil and subsoil
1.2-7.3 m	loose gravel
7.3 m	well depth

WWD 6403

0-3.8 m	claybound gravel

WWD 6407	
0-6 m	claybound gravel
6-30 m	Tarakohe Mudstone, blue-grey
WWD 6207	
0-3 m	grey clay
3-3.66 m	sand
3.66-6 m	sand, clay and gravel
6-7 m	claybound gravels
7 -7.9 m	limestone fragments
WWD 6219	
0-0.9 m	clay
0.9-3.3 m	peat
3.3-7 m	silica sand
WWD 6301	
0-11.2 m	gravel
11.2 m	solid rock
WWD 6310	
0-2 m	silt, loam
2.5.4 m	gravel, coarse sand
WWD 6316	
0-1.5 m	topsoil
1.5-1.7 m	medium sand
1.7-2.6 m	gravel, coarse-medium sand
2.6-5 m	coarse to medium sand
WWD 6003	
0-12 m	gravel, sand, cobble
12-18 m	clay, grey
WWD 6608	
0-4.5 m	gravel
4.5-40 m	Motupipi Coal Measures
WWD 6010	
0-15.5m	gravels, plus some claybound
15.6-16m	weathered horizon
16-18.1m	tidal mudflat deposits
18.2-55m	Motupipi Coal Measures

WWD 6012

0-18.6 m	gravel
18.6-146.8m	Motupipi Coal Measures

WWD 6102

0-5.7m	clay, sand
5.7 m	iron pan
5.7-10.5 m	sand
10.5 m	iron pan
10.5-12.6 m	bouldery gravel

WWD 6110

0-6 m	sand
6-7 m	iron bound clay hard pan
7-7.6 m	gravel

WWD 6113

iron pan present

WWD 6111

iron pan present

WWD 6115

0-6 m	sand
6-7 m	iron pan
7-7.3 m	gravel and boulders

WWD 6116

0-0.6 m	sandy topsoil
0.6-7.2 m	sand
7.2-10.2 m	clay bound gravel

SUMMARY DATA FOR WWD LOCATIONS		
WWD	GRID REFERENCE	RLGL
6710	NZ6 922 323	61.079
6011	NZ6 903 394	--------
6815	NZ6 956 291	--------
6808	NZ6 955 320	35.41
6814	NZ6 951 303	39.82
6821	NZ6 950 305	38.02
6601	NZ6 946 366	--------
6604	NZ6 944 359	28.55
6605	NZ6 950 359	--------
6610	NZ6 945 372	--------
6612	NZ6 945 372	--------
6615	NZ6 944 373	--------
6405	NZ6 974 377	37.860
6408	NZ6 973 383	--------
6409	NZ6 972 379	33.578
6410	NZ6 973 383	26.126
6412	NZ6 968 384	--------
6413	NZ6 968 384	--------
6418	NZ6 970 390	16.41
6422	NZ6 974 389	20.763
6423	NZ6 974 390	20.476
6224	NZ6 996 400	--------
6109	NZ6 961 415	--------
6120	NZ6 962 406	--------
6811	NZ6 952 315	33.95
6818	NZ6 951 320	29.70
6824	NZ6 954 344	28.597
6902	NZ6 937 318	34.259
6905	NZ6 945 259	--------
6906	NZ6 942 253	--------
6703	NZ6 937 245	27.623
6704	NZ6 933 349	230521
6403	NZ6 958 399	3.594
6407	NZ6 971 377	--------
6207	NZ6 991 404	22.642
6219	NZ6 003 411	--------
6301	NZ6 932 403	7.309
6310	NZ6 952 389	6.511
6316	NZ6 928 398	--------
6003	NZ6 935 420	--------
6608	NZ6 958 359	78.40
6010	NZ6 934 420	-------
6012	NZ6 911 379	--------
6102	NZ6 948 408	--------
6110	NZ6 954 420	--------
6113	NZ6 951 422	2.085
6111	NZ6 954 420	1.67
6115	NZ6 952 424	3.496
6116	NZ6 953 423	4.006

APPENDIX A-III Geophysical exploration

Geophysical exploration in the Takaka Catchment

Onshore geophysical exploration in the Takaka Catchment is limited to 2 independent surveys conducted in the Pupu Springs and Central-Lower Valley areas.

Onshore Resistivity surveys

An electrical resistivity survey at Bubbling Springs Salmon Farm, near Pupu Springs, was conducted to assess whether proposed developments were likely to lead to changes in spring flow. Results provide useful delineation of cover rocks near the Pupu Springs outlets. The principal findings were that Motupipi Coal Measures underlie the survey area, and extended at least 20 m below the ground surface. No extensive areas of saturated high resistivity rocks occurred close to the surface, which was interpreted by Broadbent (1987) that rock type in the area was either Motupipi Coal measures, deeply weathered granite, or very highly fissured granite. Alternatively it could represent a zone of brine saturated marble. The survey was conducted over 2 days in 1987.

Onshore seismic surveys

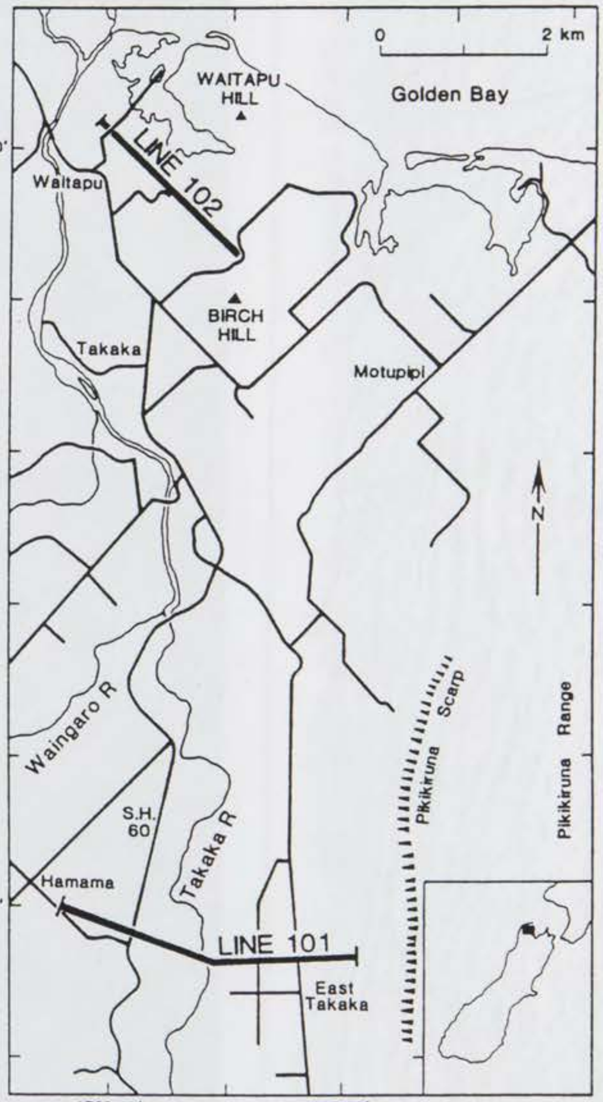
Shallow seismic reflection surveys were conducted (1987) and processed by DSIR and shot using Mini Sosie seismic reflection techniques. The survey design aimed to image the Tertiary structure, in particular the Takaka Limestone aquifer, and to delineate the "acoustic basement", primarily the Ordovician Arthur Marble and the Onekaka schist. The principle paper connected to this work, Ravens (1990), presents collection and processing information, geological interpretation, and structural interpretation information. Some conflicting and additional interpretation is presented in Judd (1989) and Mueller (1987).

In this survey three lines were conducted. One, 3.6 km long, traversed the valley from Hamama in the west to the foot of the Pikikiruna scarp at East Takaka (Line 101). The second, 2.3 km long, was shot in the northern part of the valley from Waitapu wharf in the West to the slopes of Birch hill in the south (Line 102) (Ravens (1990). The third line, located close to the main road from the bridge over the Motupipi River, was not particularly successful nor considered useful by Ravens (1989 1990). Hence it will not be discussed in this project.

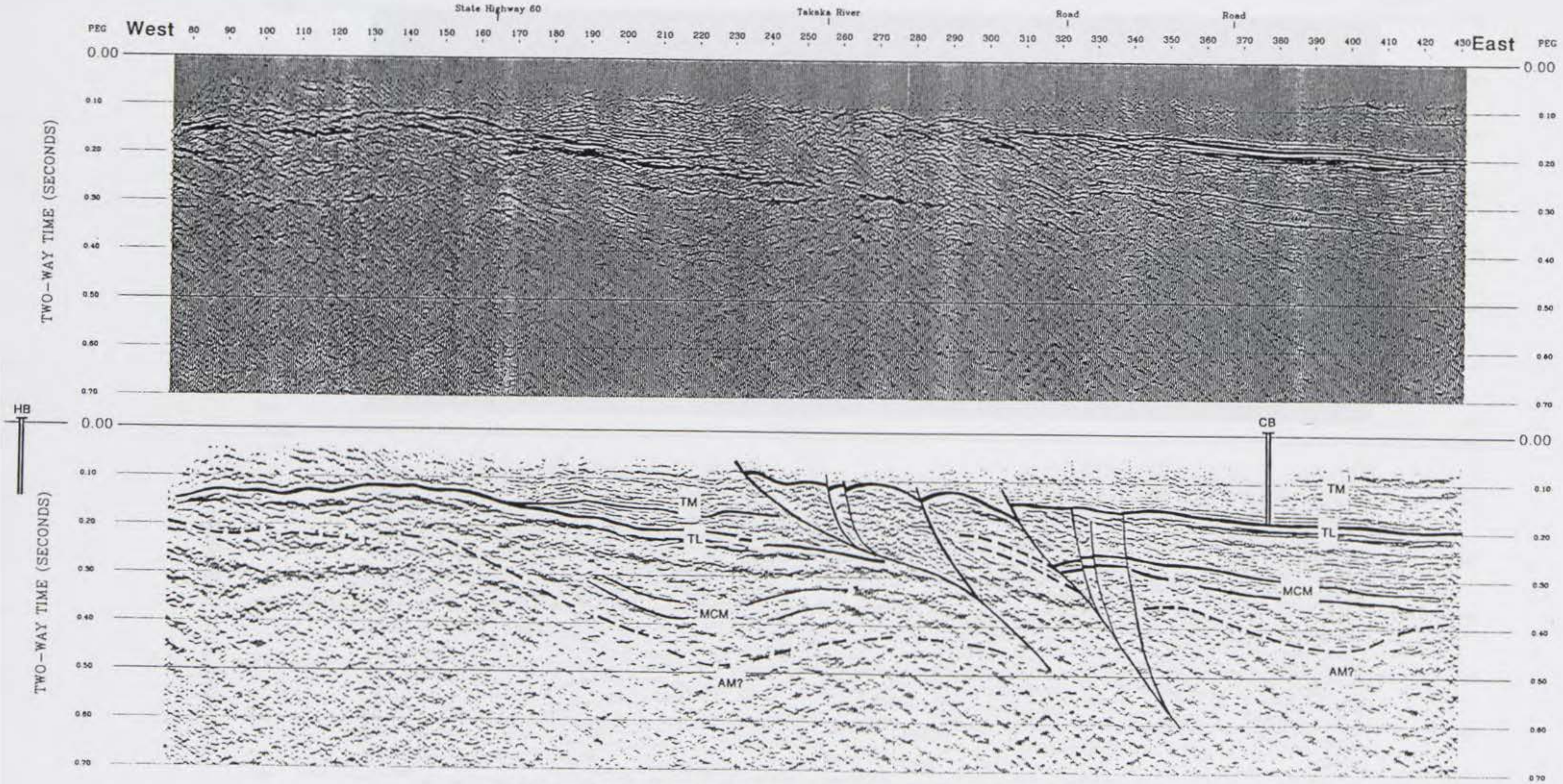
The principle finding of the survey, and in particular Line 101 was the identification of shallow low - angle thrust faulting beneath the Takaka river. As Ravens (1990) notes this could potentially provide an important hydrological connection between the karstic aquifers and overlying Quaternary gravel aquifers south of Hamama . No subsurface cavities were able to be distinguished from the seismic surveys (Ravens 1990), although they are known to exist from various bores (i.e. Couches Map reference). Line 102 showed a sequence which lies unconformably on a highly eroded basement; units have been broken by a high angle reverse fault, which is not obviously related to the low angle faults observed at East Takaka (Ravens 1990). Both fault systems support the regional NNE compressional regime (Raven 1990).

Offshore seismic surveys

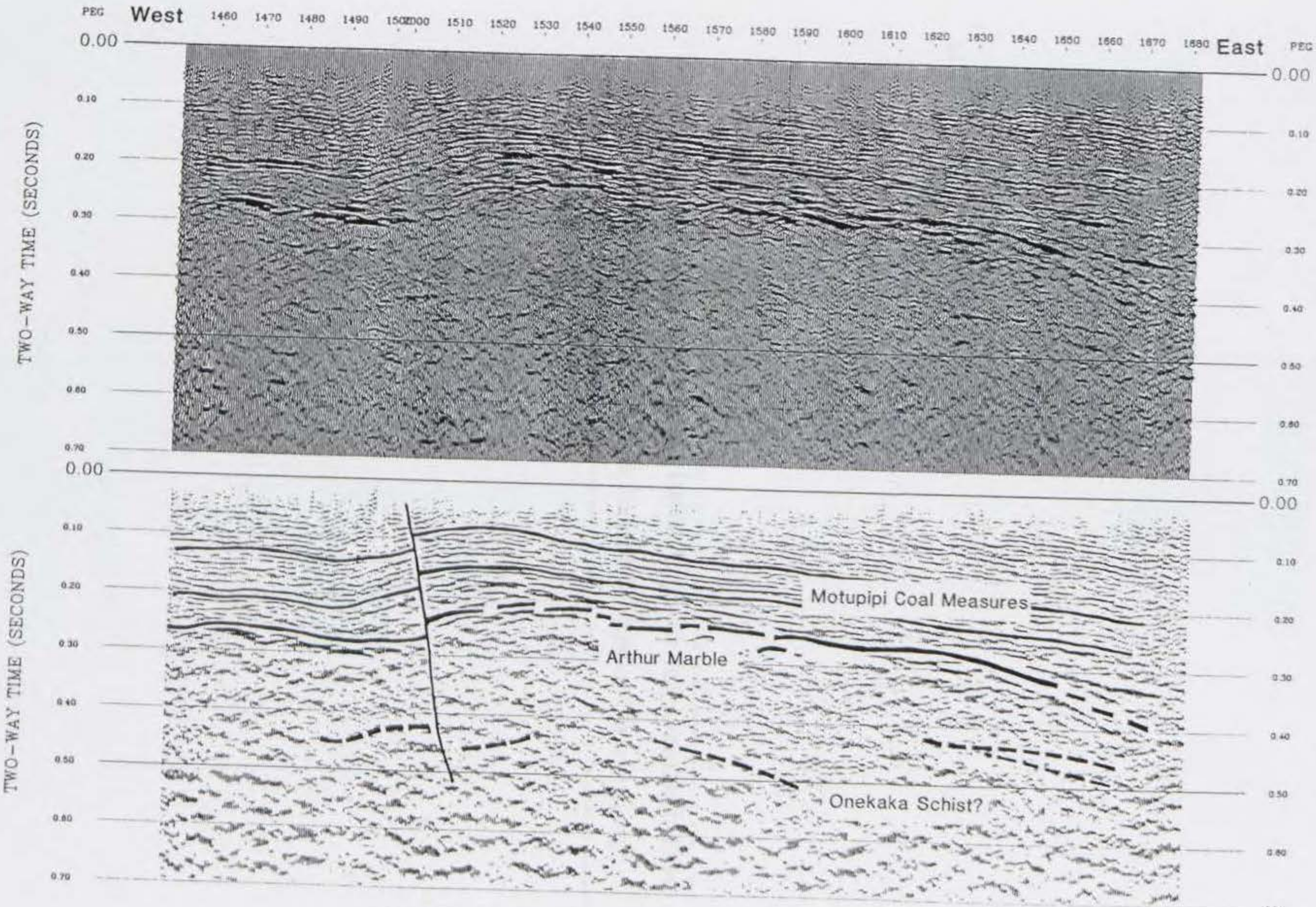
Offshore geophysical information (collected in the 1960's and 1970's by Aquitane Petreoleum New Zealand, and in the 1980's by Whitestone New Zealand) provided the basis for Thrasher's (1989) interpretation of Miocene offshore faulting in the Tasman and Golden Bays. Judd (1989) combined this existing offshore information with more recent onshore seismic information (collected by DSIR in 1987) to discuss Cenozoic deformation in the Takaka and Aorere Valleys.



Location of onshore seismic lines



Line 101 - Hamama to East Takaka, and interpretation.
TM:Tarakohe Mudstone, TL:upper surface of Takaka Limestone,
MCM:two horizons within Motupipi Coal Measures, AM:conjectural
Arthur Marble, CB:Couch's Bore, HB:Hamama Bore.



Line 102 - Waitapu Wharf to Birch Hill, and interpretation. Showing two horizons within Motupipi Coal Measures, the upper surface of the Arthur Marble, and possible reflections from the Onekaka Schist.

APPENDIX B Summary information for rainfall, flow and groundwater sites in the Takaka Catchment

SUMMARY OF RAINFALL SITES USED FOR THIS STUDY. DETAILS INCLUDE LOCATION, OPERATING SPECIFICATIONS AND PRIMARY PURPOSE(S) - ***All data was supplied by Tasman District Council, Niwa.***

SITE NAME	SITE NUMBER	GRID REFERENCE	ELEVATION	RIVER	START (YYMMDD)	CURRENT STATUS	PURPOSE	RECORDING AUTHORITY
Caesars Knob	29636	M26 759334	1445	Aorere	890816	Open	Flood	TDC
Cobb @ Trilobite	121610	M27 773088	825	Cobb	690430	Open	Power station	NIWA - Nelson
Cobb @ Dam	na	M26 835110	823	Cobb		Open	Power station	ECNZ
Cobb @ Power station	na	M26 877129	213	Cobb		Open	Power station	ECNZ
Happy Sams	152903	M26 889356	150	Anatoki	901031	Open	Power station	TDC
Hanging Rock	152904	M26 889296	85	Waingaro	880817	Open	Res, Flood	TDC
Takaka Hill	120936	N26 969194	675	Riwaka	800110	Open	Resource	TDC
Canaan	29910	N26 900850	850	Marahau		Open	Resource	TDC
Takaka Depot	28802	N26 938375	15	Takaka	700831	Closed (921124)*	Res, Flood	TDC
Kotinga	152901	N26 938373	10	Takaka	920501	Open	Res, Flood	TDC
Harwoods	152902	N26 930195	130	Takaka	880125	Open	Resource	TDC/NIWA - Nelson
Motupipi	29836	N26 970386	20	Motupipi	811002	Closed (880120)*	Resource	TDC
East Takaka	29837	N26 960348	120	Takaka		Closed	Resource	TDC
Tarakohe	na	N25 016425	5	Takaka		Closed	Resource	
Uruwhenua	na	N26 946240	91	Takaka		Closed	Resource	
Takaka Airfield	na	M25 889447	30	Takaka		Closed	Resource	
Pupu power house	na	M25 898400	15	Waikoropupu		Open	Resource	
Salmon Farm @ Springs	na	N26 908400	13	Waikoropupu		Open	Resource	
Pupu @ Takaka	na	M26 878396	4	Waikoropupu		Closed (	Resource	
Parapara	na	M25 848490	0	Takaka/Onekaka		Closed	Resource	
Patons Rock	na	M25 889460	3	Onekaka		Closed	Resource	
Mt Snowden	120637	M26 767190	1530	Waingaro		Closed (930525)	Flood	TDC

SUMMARY OF FLOW SITES USED FOR THIS STUDY. DETAILS INCLUDE LOCATION, OPERATING SPECIFICATIONS, PRIMARY PURPOSE(S) - ***All data was supplied by Tasman District Council, Niwa.***

SITE NAME	SITE NUMBER	GRID REFERENCE	RIVER	CATCHMENT	START (YYMMDD)	CURRENT STATUS	PURPOSE	RECORDING AUTHORITY
Takaka @ Harwoods	52902	N26 930195	Takaka	Upper Takaka	621231	Open	Res, Major River	NIWA/TDC
Takaka @ Kotinga	52901	N26 939373	Takaka	Central Takaka	701008	Open	Res, Flood, Eng	TDC
Anatoki @ Happy sams	52903	M26 889356	Anatoki	Anatoki	790905	Open	Res, Flood, Eng	TDC
Waingaro @ Hanging Rock	52904	M26 889296	Waingaro	Waingaro	790905	Open	Res, Flood, Eng	TDC
Cobb @ Trilobite	52916	M27 773088	Cobb	Upper Takaka	690501	Open	Resource	NIWA
Waikorpupu Springs @ Springs River	52907	N26 907399	Springs	Waikoropupu -	741203	Open	Resource	TDC
Waikoroupu @ Bubbling springs	52906	N25 908405	Springs	Waikoropupu -	850501	Open	Res (S Farm)	TDC
Fish Creek @ Waikoropupu Springs	52910	N26 905397	Fish Creek	Waikoropupu -	850501	Open	Resource	TDC
Elm Grove @ Spring Brook River	52912	N26 933312	Spring Brook	Takaka	910529	Open	Resource	TDC
Rameka @ Pages Cut	52913	N26 997327	Rameka Creek	Central Takaka	930514	Open	Res, Eng (Hydro)	TDC
Waikoropupu River @ Egdirb	52908	N25 912405	Waikoropupu	Waikoropupu -	811125	Closed (870907)	Resource	TDC
Waikoropupu @ Main spring	52909	N26 906398	Springs	Waikoropupu -	841296	Closed (860902)	Resource	TDC
Waitapu @ Wharf	52900	N25 938426		Takaka	791016	Closed (910515)	Tidal, Eng	TDC
Tekakau @ spring	52911	N26 935398		Takaka	840911	Closed (861125)	Resource	TDC
Takaka River @ Pages Cut	52905	N25 927406	Takaka	Takaka	811208	Closed (900308)	Flood, Eng	TDC
Riwaka @ South Branch	56901	N26 034172	Riwaka	Riwaka	611201	Open	Resource, Flood	TDC

SUMMARY OF GROUNDWATER SITES USED FOR THIS STUDY- DETAILS INCLUDE LOCATION, AQUIFER, OPERATING SPECIFICATION AND PURPOSE(S) - ***All data was supplied by Tasman District Council, Niwa.***

SITE	SITE NUMBER	GRID REFERENCE	AQUIFER	DEPTH (m)/ CASING (m)	START (YYMMDD)	CURRENT STATUS	PURPOSE	REDUCED LEVEL
Pupu @ Balls - WWD 6011	6011	N26 902394	Arthur Marble	114/ until 35 m	940601	Open	Resource	21.299
Hamama -WWD 6710	2970710	N26 921324	Arthur Marble	85	880524	Open	Resource	61.628
C'serneys -WWD 6418	2880418	N26 969389	Takaka Limestone	45.7	871028	Open	Resource	16.893
Grove Orchard	2880224	N26 996399	Takaka Limestone	50/ until 21.4 m	871028	Blah	Resource	45.986
Bennetts - WWD 6815	2980815	N26 956291	Takaka Limestone	48.8/ until 40 m			Resource	
Jardines	2890001	N25 951422	Takaka Limestone	6	870930	Closed (871028)	Water rights	
Jeffersons	WWD 6829	N26 942309	Takaka Limestone	21			Water rights	

na = not available, blank spaces denotes no information was available

APPENDIX C-I River flows

Low and High Flows of Major Rivers

Minimum flows for the 5 main rivers are given in the table below. Low flow periods are of particular interest in the Takaka Catchment, as this is when the complex river-aquifer interaction and role of the karstic geology are most apparent. The Takaka and Waingaro Rivers both cross major loss zones, as do the majority of the minor contributing streams and creeks that drain the foothills of the eastern and western ranges. The Takaka River runs dry for a section downstream of Lindsays Bridge (N26 952260) to Spring Brook (N26 933312) for approximately 100 days of the year.

	Takaka River @ Harwoods	Waingaro River @ Hanging Rock	Anatoki River @ Happy Sams	Waikoropupu River	Cobb River @ Trilobite
7 - day low flow	1683 l/s @ 900302 90000	3283 l/s @ 920403 153000	1686 l/s @ 930213 43636	3736 l/s @ 920501 203000	345 l/s @ 900302 90000
Minimum flow	963 l/s @900408 223000	3050 l/s @ 920507 90000	1491 l/s @ 930219 94326	3580 l/s @ 920506 173000	316 l/s @ 900308 201500

The above table presents minimum 7 - day low flow and instantaneous minimum flow periods for the Takaka River and tributaries from 1990 - 1997. 7 - day low flow figures are calculated using the method of moving averages and non overlapping intervals. Time is given in standard yymmdd hhmmss format and represents the time at which the specified interval begins. The second row of data represents the minimum instantaneous flow recorded at the stated time. All figures are in l/s. Flow figures are derived from each rivers principal monitoring site.

Maximum river flows recorded in the Takaka catchment occurred during the July 1983 floods, when river flows in the Takaka River @ Harwoods recorded a stage value of 689 mm. This resulted in extensive damage downstream to farmland, the Takaka Township and major structural features such as Kotinga Bridge. Other major flood periods for the three main rivers in the catchment are detailed in the table below.

Date	Largest flood and date	Second largest flood and date	Third largest flood and date
Takaka River @ Harwoods	689 (4.8 m) @ 830710	596 (4.6 m) @ 680309	527 (4.3 m) @ 750313
Anatoki River @ Happy Sams	608 (5.3 m) @ 881229	572 (5.1 m) @ 760409	562 (5.1 m) @ 750401
Waingaro River @ Hanging Rock	1296 (5.8 m) @ 680314	1124 (5.6 m) @ 670814	941 (5.0 m) @ 760414

APPENDIX C-II Summary of existing gauging database

GAUGING DATA FOR THE TAKAKA RIVER BETWEEN THE HARWOODS RECORDER AND PAYNES FORD(1988-1998) - *All Data collected by the NMRC, Tasman District Council. All flow figures quoted in l/s.*												
SITE	**GRID**	**Date of survey**										
DETAILS	**REFERENCE**	**881122**	**880419-20**	**890426-28**	**900308**	**910123**	**910304**	**910621**	**960125-26**	**960401-02**	**970317-18**	**98 Blah**
Harwoods	N26 9310195		8700	2040	1751	10030	5900	8969	10810	2655	2675	
u/s Kill Devil Ck	N26 939205					9567						
Harts	N26 951217					9169						
Lindsays Bridge	N26 946243	4683	8598			9232	5999	7855	10036	2348	1840	
Sparrows	N26 952248					8114		6942	9813	1474		
Bottom of Sparrows	N26 952265					6643						
u/s Craigieburn Ck	N26 953274	378	4171			4036		3436				
Opposite Spittals	N26 950266					2685						
d/s of Gorge Ck	N26 943296					1080						
u/s of Stoney CK	N26 939301					714						
u/s of Springbrook confluence	N26 943323					0						
d/s of Springbrook confluence	N26 942333					465						
End of Hamama Straight	N26 941342					417		0				
Paynes Ford bridge	N26 939359		2174	577	257	830	520	269	8682	952	347	

GAUGING DATA FOR MINOR TRIBUTARIES OF THE TAKAKA RIVER AND MISCELLANEOUS SPRINGS (1998 - 1998) - *All data collected by the NMRC, Tasman District Council. All flow figures quoted in l/s.*												
SITE	**GRID**	**Date of survey**										
DETAILS	**REFERENCE**	**881122**	**880419-20**	**890426-28**	**900308**	**910123**	**910304**	**910621**	**960125-26**	**960401-02**	**970417-18**	**98 Blah**
Elm Grove spring @ Spring brook	N26 937316		1073	0	0	592	0	0	1658	71	0	
Spittal spring @ outlet	N26 955287			44	27			68	462	184	0	
East Takaka springs	N26 943349								287		120	
East Takaka stream @ Rhodes	N26 942348									82		
Ironstone Creek @ confluence	N26 954247			29	52		40	0	145	104	40	
Craigieburn u/s of water take	N26 924263			105	52		115	49	140	121	61	Blah
Gorge Creek u/s of water take	N26 975289											Blah

GAUGING DATA FOR THE WAINGARO RIVER (and principal tributaries) BETWEEN HANGING ROCK RECORDER AND THE CONFLUENCE OF THE TAKAKA RIVER - *Data collected by the NMRC and Tasman District Council. All flow figures are quoted in l/s.*

SITE	SITE	GRID	Date of survey												
NUMBER	DETAILS	REFERENCE	721214	730301-02	730327-28		880419-20	890426-28	900308	910304	910621	920619	960125-26	960401-02	970317-18
1	Hanging rock	M26 889296	10200	2750	2750		5667	4653	3615	9147	3954	10000	9969	6800	3638
2	Bottom of Larry Pettersons	M26 896305		3210						8691			8961	6284	3847
3	Below Commune	N26 904314											9432	6404	3462
4	Savages Pumpshed	N26 912333								8173	3341		8910	6278	3394
5	Cemetry Road	N26 930350											9910	6395	3317
6	Tasman Kiwifruit Limited	N26 934358								8080			9128	6242	3035
7	Above Takaka confluence	N26 938360	10170		2099		4819	4050	2254	8460	3133	9747	9329	5973	3108
8	Little Waingaro @ Road end	M26 893317												61	12

GAUGING DATA FOR THE ANATOKI RIVER (and principal tributaries) BETWEEN THE HAPPY SAMS RECORDER AND THE CONFLUENCE OF THE TAKAKA RIVER - *Data collected by the NMRC and Tasman District Council. All flow figures are quoted in l/s.*

SITE	SITE	GRID	Date of survey												
NUMBER	DETAILS	REFERENCE	721214	730301-02	730327-28	820419-20	880419-20	890426-28	900308	910304	910621	920619	960125-26	960401-02	970317-18
1	Happy Sams Commune	M26 867346				3500	2540	2483	1376					3077	1785
2	Happy Sams recorder	M26 889356				3500	3120	3706	1822	5755	2877	5645	5561	5009	3020
3	Holmwood sawmills	M26 897361		1850		3780				5914	2705		5899	4255	2539
4	Bencarri Swing bridge	N26 908360				3780							5486	4392	2527
5	Top end of One Spec Rd	N26 911366	5780										5161	4165	2360
6	Middle of One Spec Rd	N26 919367	5980	1320	2080					5777			5479	4216	2475
7	One Spec bridge	N26 931380	6430		1800		3133	2678	1475	5161	2239	5341	5656	3854	2061
8	Go ahead Ck @ Anatoki bridge	N26 928380											98	65	24
9	Go ahead Ck-Anatoki confluence	N26 927373											93	49	0
10	One Spec Ck @ bridge	N26 927380												71	

GAUGING DATA FOR THE LOWER TAKAKA RIVER FROM PAYNES FORD TO PAGES CUT - *Data collected by the NMRC and Tasman District Council*					
SITE DETAILS AND GRID REFERENCE	**PAYNES FORD**	**D/S OF WAINGARO CONFLUENCE**	**KOTINGA**	**RILEYS ROAD END**	**PAGES CUT**
	N26 940358	N26 940364	N26 939373	N26 932 384	N25 927406
Date of survey	*All flow figures are quoted in l/s*				
820419-20			8950		10200
850527			4330		8130
851009-10			12090		18130
880419-20	2174		7265/7297		9791
890426-28	577		4682		7572
900308	257		2701		5227
910123	830		10250		
910304	520		8370		
910621	269		3794		
920619					
960125-26	8682		16122		24730
960401-02	952		7512		12270
970317-18	347		4551		
9803 Blah					

APPENDIX D-I Mean annual rainfall data

Rainfall Correlation Details

Many rainfall recorder stations in the Takaka Valley have only limited records. To extend records for sites with limited rainfall records, correlations are performed with adjacent or nearby stations following procedures outlined in WMO (1983). Where applicable rainfall normals derived from the period 1961 - 1990 (Tomlinson and Sansom 1994), or 1951-1980 (NZ Met service), are applied. Rainfall normals allow for fair comparison of the rainfall at different places, for a standard period (monthly or annual).

1. Little Devil Tarn

Existing record length 930601 to present. Correlated with Bainham Station (Aorere Valley) to create a generated record of 50 years.

2. Caesars Knob

Existing record 1990 to present. Used Boulder Lake data to derive mean annual rainfall figure. It is recognised that both Casears Knob and Little Devil are in exposed locations, and rainfall information should be used cautiously for resource issues.

3. Takaka at Harwoods

Existing record 1988 to present. Correlated with Takaka Depot to create generated record of 20 years.

4. Waingaro at Hanging Rock

Existing record 1988 to present. Correlated with Takaka Depot to create generated record of 20 years.

5. Anatoki at Happy Sams

Existing record 1990 to present. Correlated with Takaka Depot to create generated record of 20 years.

6. Motupipi

Existing record 1981-1983. Correlated with East at Hills to create generated record of 20 years.

7. Canaan (Marahau)

Existing record 1994 to present. Correlated with Riwaka at Takaka Hill to create generated record of 16 years.

8. Parapara, Paton Rock, Takaka Airfield, Pupu at Takaka, Takaka

Figures taken from Rainfall normals 1951 - 1970.

9. Cobb power station, Cobb dam, Tarakohe, Uruwhenua

Figures taken from rainfall normals 1961 - 1990.

10. Takaka Depot, Takaka hill, Kotinga, East Takaka at Hills

Used length of data of existing records

Summary table of derived mean annual rainfall for sites in the Takaka Catchment and surrounds

SITE	LENGTH OF RECORD	MEAN ANNUAL RAINFALL (MM)
Little Devil @Tarn	51	3781
Caesars Knob	na	5140
Cobb @ Dam	30	2246
Cobb @ Power station	30	2052
Happy Sams	19	3350
Hanging Rock	19	3066
Takaka Hill	16	2441
Canaan	16	3479
Takaka Depot	na	2011
Kotinga	na	2121
Harwoods	18	2046
Motupipi	na	2338
East Takaka	na	2042
Tarakohe	30	1542
Uruwhenua	30	2278
Takaka Airfield	30	2107
Pupu @ Takaka	30	3218
Parapara	30	2236
Patons Rock	30	1983

na = not available

APPENDIX D-II The areal isohyetal method

Isohyetal Method

The calculation of isohyets (i.e. contours of equal rainfall depth) is a reliable method of estimating average precipitation for a watershed, but results rely on the individual contouring and on a knowledge of storm morphology. However, if the precipitation values between precipitation station locations are determined by linear interpolation, the differences in average values should be reduced. The isohyetal calculations are well adapted for visual display. The area between each isohyet within the watershed is determined, and an average precipitation value is calculated. The isohyetal average is calculated as

$$P(ave) = \sum_{i=1}^{n} W_i P_i$$

where $P(ave)$ = isohyetal average precipitation (mm)

P_i = isohyetal cell average precipitation (mm)

$W_i = A_i / A$, A_i - area of cell (km_2)

A = total area (km_2)

n = total number of cells

SOILS OF THE TAKAKA LOWLANDS (O'Byrne 1983)					
DESCRIPTION	**TYPE**	**OCCURRENCE**	**DERIVATION**	**CHARACTERISTICS**	**LANDUSE**
Soils of coastal sand dunes	Tahunanui sand (Tu, Tug)	Low coastal dunes and sand flats on the narrow spit east of the Takaka River	Wind blown sand of mixed provenance	Moderately-strongly leached, yellow-brown sand, simple profiles, excessive drainage, rapid permeability	Rough pasture, scrub, holiday homes, limited horticulture
Soils of river flats	Karamea silt loam (Kr)	River flats of low terraces in Takaka River Valley and Anatoki and Waingaro	Mixed alluvium, marble, argillite, schist tertiary sediments	Strongly leached, well drained, moderately permeable, variable pattern, hygrous	Dairying and grazing, market gardening, suitable for irrigat-ion, variable soil pattern
Soils of low terraces and benches	Hamama stoney silt loam (Ha)	Low terrace on either side of Takaka River Valley, above junction with Waingaro River, (30-90 m in Hamama, 150 m in Upper Takaka	Formed on unweather-ed rounded gravel alluvium, derived argill-ite, greywacke, schist	Strongly leached, hygrous, excessive drainage, rapid permeability, friable, stoney of moderate depth	Intensive grazing and dairying, suitable for some horticultural tree crops, high potential food value production
	Puramahoi silt loam (Pu)	Low flat, gently sloping terraces in Puramahoi and Motupipi (up to 30 m).	Mixture, marble, lime-stone, schist, granite tertiary sediments	Hygrous to hydrous, stronly -very strongly leached, intergrades between granular loams and yellow brown earths, well drain-ed, moderately deep	High production, mainly dairy-ing and grazing, suitable for all land uses, high suitability for irriagation, low nutrient status
Soils of intermediate terraces and fans	Kotinga silt loam (Kt)	Undulating low fans at Kotinga	Gravel alluvium and fines derived argillites, greywacke, schist, marble, with no iron pan	Very strongly leached, podzolised, hydrous, poorly drained, thick topsoil, weakly developed structure, best example of Pakihi land in Golden Bay	Severe drainage problems, strongly acidic, low nutrients, dairying, high fertiliser require-ments, only marginally suitable for irrigation
Soils of high terraces, fans and benches	Onahau sandy loam (On)	Isolated terraces and benches on western side of the Takaka River, from Upper Takaka to Golden Bay	Coarse gravels, schist, marble, argillite, granite	Variable, strongly leached podzolised yellow-brown earths, slight iron pan, hydrous, poor drainage, low nutrient status	Unsuitable for most horticultur-al or field crops, only marginal for irrigation, moderate poten-tial for food production
	Tarakohe sandy loam (Th)	High benches south of Tarakohe, Motupipi Stream, up to 150 m elevation	Limestone and calc-ereous sandstone or siltstone	Hygrous, weakly-moderately leached rendzina soils, moderate permeability, erosion is negligible	Semi-intensive grazing lands, droughtiness may be a limitation suitable pasture, less suitable for horticulture and field crops
	Rameka silt loam (Rm)	Irregular undulating slopes, altitude varies 30-120 m	Weathered coarse gravel, volcanic rocks, and marble	Hygrous, deep soils, friable brown top-soils	Semi-intensive grazing lands, horticulture at lower levels, few limitations for landuse
Soils of rolling and hilly land	Otere silt loam (Ot)	Low rolling and hilly land, west of Motupipi Stream, up to 180 m	Soft tertiary sediments	Hydrous to hygrous, strongly to very strongly leached, yellow-brown earths	Some exotic forest plantations, dairying or grazing, scrub
	Otere hill soils (OtH)	Hilly or moderately steep slopes on soft tertiary sediments	Soft tertiary sediments	Well drained, range up to 330 m, prone to slight sheet and slip erosion	Semi-entensive grazing lands, forestry, low value for food production
	Onekaka hill soils (OnH)	Low hilly areas, near the mouth of the Takaka River	Schistose-greywacke	Hygrous to hydrous, strongly -very stron-gly leached, variable depth	Some pasture, reversion to scrub

APPENDIX E DESCRIPTION OF SOILS IN THE TAKAKA VALLEY

APPENDIX F-I Waikoropupu Spring data

Spring Data Generation and Summary Statistics for WAM.

In order to deduce the Main Springs discharge of WAM the following calculation is used:

Main Springs Discharge = Springs River Flow + Salmon Intake - Fish Creek Springs Flow.

The mean total spring flow of 13253 l/s is composed of 77 % Pupu Springs flow (Main Springs and Dancing sands discharge) and 23 % Fish Creek Springs.

The following table contains Waikoropupu Springs discharge data. All figures are given in l/s. Data period for Mean values is 900417 - 970923. Data period for maximum and minimum values is 940601 - 970923.

	Main Spring	FishCreek Spring	Total springs
Mean spring Flow (l/s)	Blah	3304	13253
Maximum spring flow (l/s)	12546 (950930 @ 11500)	6961 (950930 @ 11500)	19510 (950930 @ 11800)
Minimum spring flow (l/s)	7312 (97040 @ 144500)	0 on numerous occasions	7312 (970407 @ 144500)

During this period data is derived for Main Spring , Fish Creek Springs and the total spring flow from Balls groundwater site. This eliminates errors incurred when calculating spring flow using the river recorder site data. It also has the advantage of presenting Fish Creek Springs data with overland flow already removed from the record.

APPENDIX F-II Spring data manipulation

Deriving an average annual value for total spring discharge

1. First, generate record of Fish Creek flow (minus the overland/surface component)

a) pdist → 52910 Fish Creek with surface flow

mean = 3982.28 l/s

When measured by Balls this doesn't include surface flow.

pdist → 26011 Fish Creek generated by Balls

mean = 3621.26 l/s (940601-970923)

b) difference between Fish Creek (surface flow) and Fish Creek (no surface component)

= 3982.28 - 3621.26

= 361.02

c) apply the difference to the long term record (900417-940601)

pdist → 52910(Fish Creek surface flow)

= 3982.28 - 3621.26

= 3047.56

This figure represents Fish Creek contribution (900417-940601).

2. Secondly, generate a mean figure for pre-Balls period (i.e. 900417-940607) for total spring flow.

pdist→222 (Main Springs)

= 9821.30 + 3047.56

total spring flow = 1268.86 l/s (900417-940601)

3. Thirdly, generate a mean value for site 36071 (total spring flow derived from Balls)

= 13794.9 l/s

4. Fourthly, to generate a long-term mean, weight the two periods by the length of record in each

$$12868.86 \times 50/91 = 7037.84$$

$$13794.9 \times 41/91 = 6215.28$$

$$7037.84 + 6215.28 = 13253.12 \text{ l/s}$$

This figure represents long-term mean total flow (900417-971030).

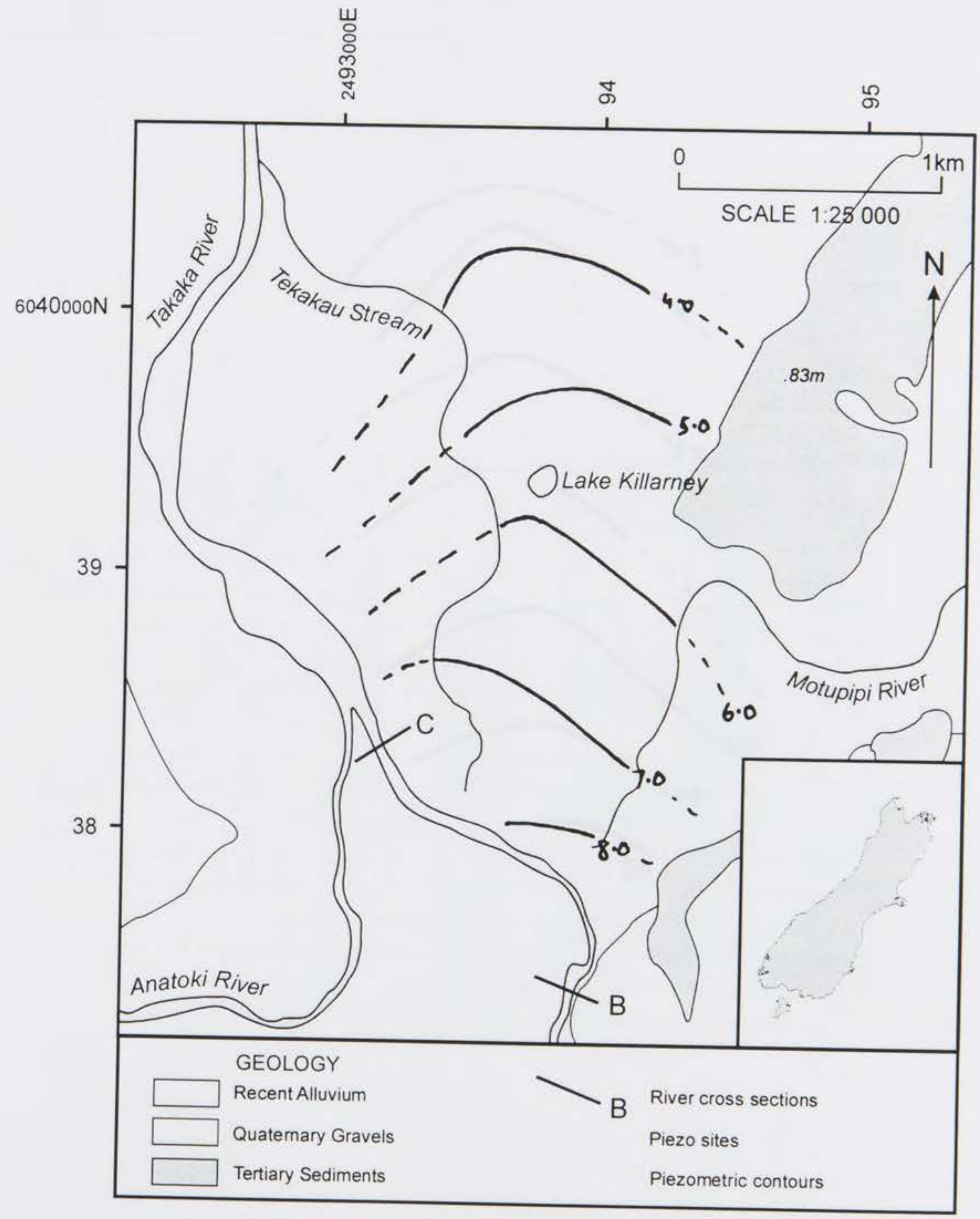
APPENDIX G-I Water level survey results for the ETML Aquifer

RESULTS FOR THE ETML AQUIFER POTENTIOMENTRIC SURVEYS - 1997					
SITE NO	GRID REFERENCE	WWD	12-Jun	16-Sep	12-Dec
1	N26 951303	6814	32.72	35.06	32.51
2	N26 950305	6821	31.89	33.95	31.49
3	N26 955320	6808	27.05	28.19	27.02
4	N26 944359	6604	21.19	21.89	21.27
5	N26 974377	6405	10.07	18.06	ns
6	N26 972379	6409	10.02	14.81	ns
7	N26 972383	6410	10.64	10.87	ns
8	N26 977384	6411	10.39	ns	ns
9	N26 972389	6419	7.49	10.23	ns
10	N26 970390	6418	8.14	11.70	ns

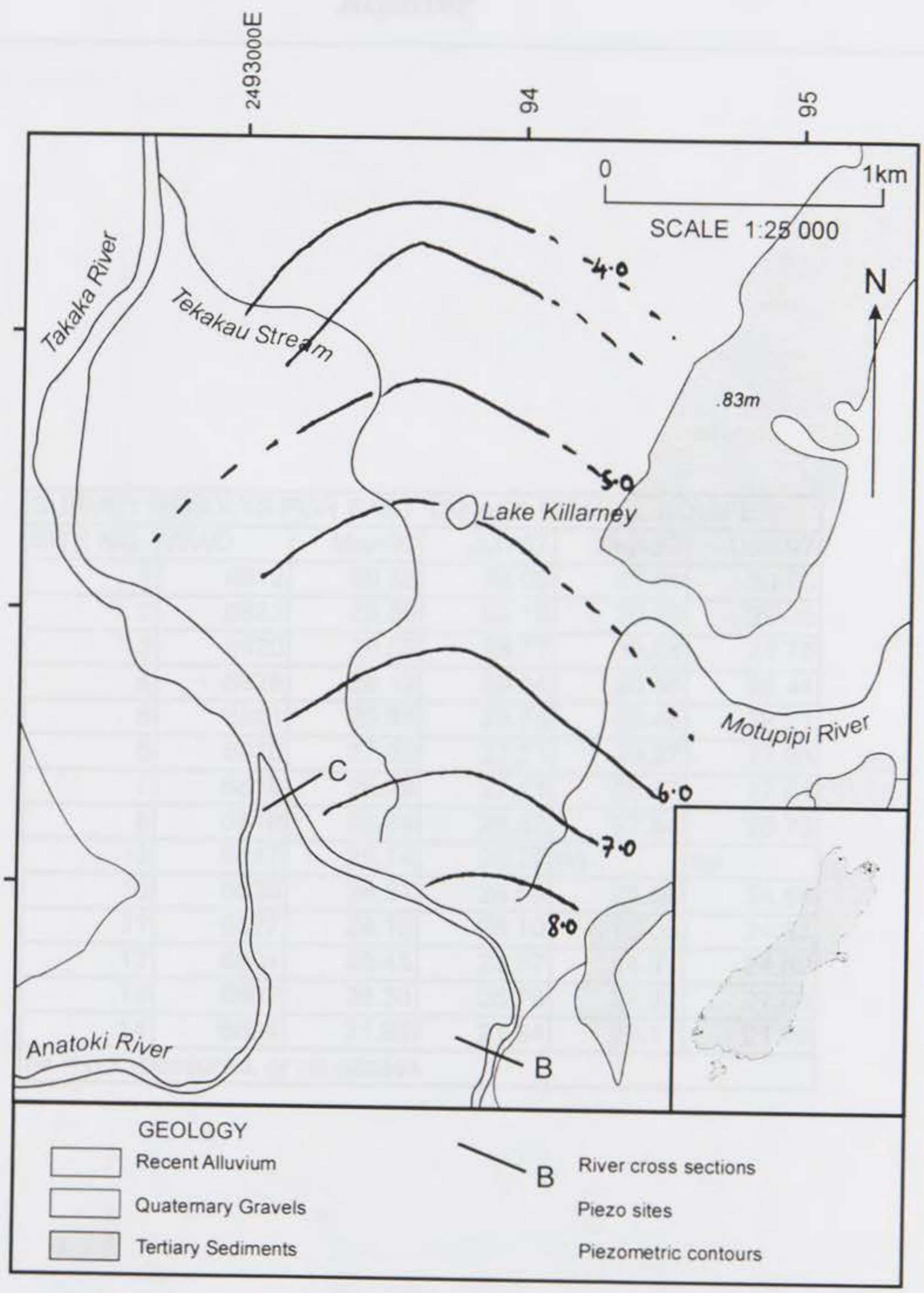
ns = not sampled

APPENDIX G-II Water level survey results for the TTG Aquifer

REDUCED LEVEL WATER LEVELS FOR THE TAKAKA TOWNSHIP GRAVEL AQUIFER				
SITE NO	**WWD/FH**	**Jan-98**	**Mar-98**	**Aug-98**
1	6323-P1		7.93	8.36
2	6325	7.79	7.39	na
3	FH2	7.07	7.10	7.47
4	FH26	7.05	7.16	7.50
5	FH25	6.86	7.02	7.38
6	FH1	7.13	7.25	7.61
7	FH3	6.66	6.75	na
8	6312	na	5.97	6.45
9	6326	6.13	6.23	6.42
10	6323-P2	na	6.48	na
11	FH4	6.29	6.36	6.60
12	FH5	6.00	6.10	6.33
13	FH6	5.56	5.69	5.97
14	FHVET	5.51	5.62	5.97
15	6327	5.50	5.63	5.98
16	FH10	4.97	5.15	5.56
17	FH7	4.99	5.16	5.50
18	FH8	4.63	4.83	5.18
19	FH9	4.40	4.60	4.94
20	FH11	4.53	4.72	5.12
21	FH15	5.81	5.82	5.83
22	FH17	3.94	4.13	4.53
23	6314	4.08	4.28	4.66
24	6323-P3	na	5.53	na
25	FH13	3.66	3.90	na
na = not measured, or no access				



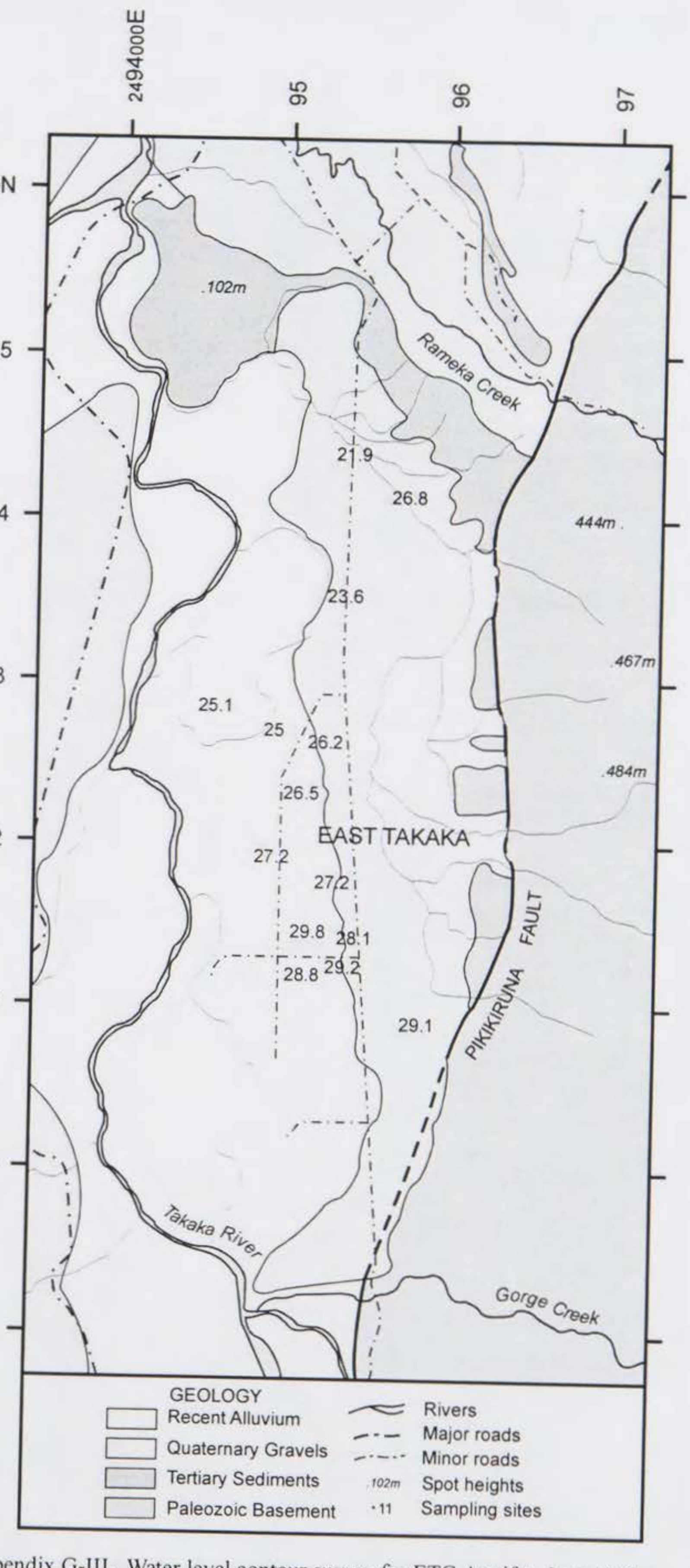
Appendix G-II Water level contour map for TTG Aquifer, January 1998 survey



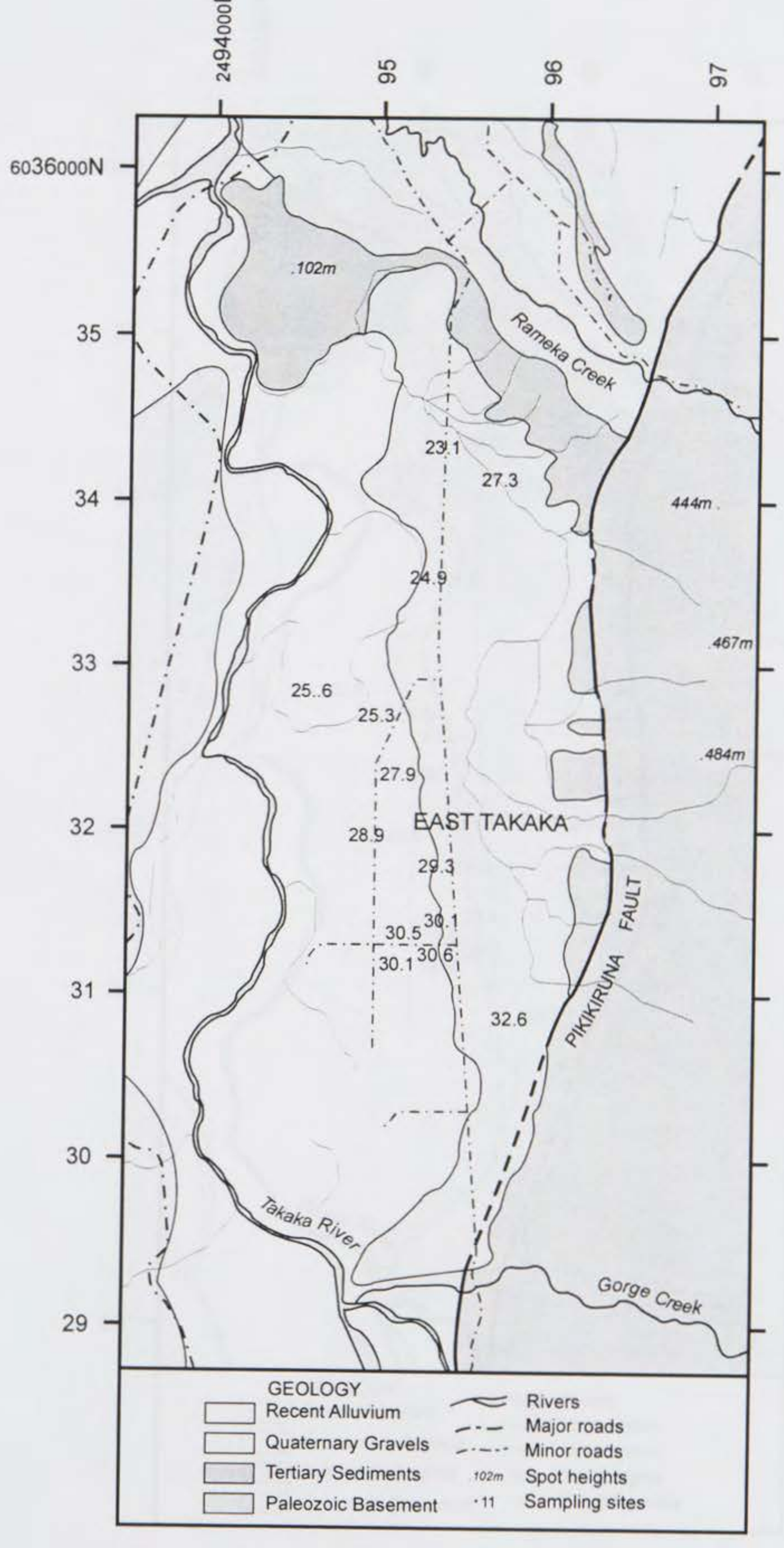
Appendix G-II Water level contour map for TTG Aquifer, August 1998 survey

APPENDIX G-III Water level survey results for the ETG Aquifer

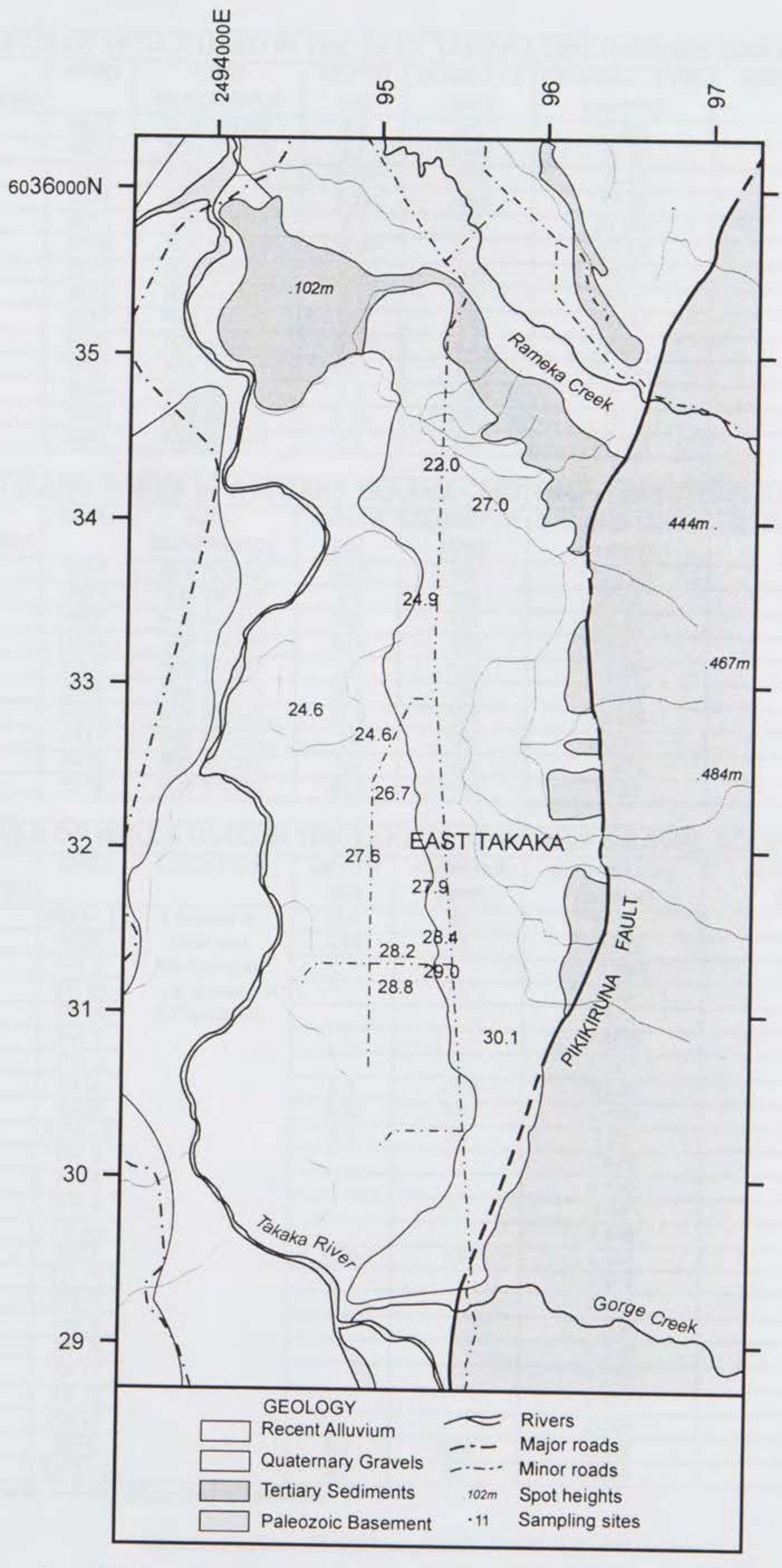
SURVEY RESULTS FOR EAST TAKAKA GRAVEL AQUIFER					
SITE NO	WWD	Mar-97	Jun-97	Sep-97	Dec-97
1	6812	29.35	29.09	32.64	30.08
2	6823	28.30	29.18	30.59	29.05
3	6820	28.59	28.77	30.96	28.75
4	6828	28.12	28.14	30.36	28.44
5	6811	29.81	29.76	30.46	28.21
6	6810	27.66	27.21	29.27	27.95
7	6819	26.29	27.21	28.87	27.61
8	6818	25.94	26.52	27.84	26.75
9	6817	25.74	26.22	na	na
10	6826	24.31	24.99	25.33	24.58
11	6827	24.19	25.10	25.55	24.63
12	6804	23.45	23.57	24.91	24.89
13	6802	26.36	26.76	27.32	27.00
14	6824	21.98	21.94	23.11	21.99
na = not measured, or no access					



Appendix G-III. Water level contour survey for ETG Aquifer, June 1997 survey



Appendix G-III. Water level contour survey for ETG Aquifer, September 1997 survey



Appendix G-III. Water level contour survey for ETG Aquifer, December 1997 survey

DETAILS OF WELLS USED IN THE EAST TAKAKA UNCONFINED GRAVEL AQUIFER						
SITE NUMBER	WWD	GRID REFERENCE	DEPTH (m)	DIAMETER (MM)	GROUND LEVEL (mamsl)	REDUCED LEVEL (mamsl)
1	6812	N26 956309	9.8	300	37.527	37.527
2	6823	N26 954313	5.1	1000	34.36	33.91
3	6820	N26 951316	6.93	900	34.55	34.75
4	6828	N26 953315	6.32	1000	33.25	33.42
5	6811	N26 952315	7.1	75	33.952	33.952
6	6810	N26 954319	4.9	300	31.02	31.209
7	6819	N26 949319	7.3	100	30.7	30.97
8	6818	N26 951320	6.9	50	29.7	29.305
9	6817	N26 951323	2.7	50	29.047	29.047
10	6826	N26 950327	6.75	50	28.082	27.832
11	6827	N26 945328	8.67	50	27.834	28.134
12	6804	N26 952335	5.6	1050	27.1	27.175
13	6802	N26 955342	4.24	1050	29.6	30.005
14	6824	N26 954344	14	150	28.579	28.885

WELLS AND BORES IN THE EAST TAKAKA - MOTUPIPI LIMESTONE AQUIFER						
SITE NUMBER	WWD	GRID REFERENCE	DEPTH (m)	DIAMETER (MM)	GROUND LEVEL (mamsl)	REDUCED LEVEL (mamsl)
1	6814	N26 951303	44.8	150	39.825	40.025
2	6821	N26 950305	64	150	38.02	38.164
3	6808	N26 945320	125	150	35.41	35.684
4	6604	N26 944359	42.6	100	28.55	29.059
5	6405	N26 974377	107	100	37.86	38.202
6	6409	N26 972379	32.9	150	33.578	34.036
7	6410	N26 973383	71.9	125	26.126	26.436
8	6411	N26 977385	21	100	22.063	22.363
9	6419	N26 972390	18	100	16.874	16.874
10	6418	N26 970390	45.7	100	16.41	16.893

DETAILS OF WELLS USED IN THE TAKAKA TOWNSHIP GRAVEL AQUIFER						
SITE NUMBER	WWD	LOCATION	DEPTH (m)	DIAMETER (MM)	GROUND LEVEL (mamsl)	REDUCED LEVEL (mamsl)
1	6323 - 1	Location of wells and fire hydrants is shown in Figure 4.8	6.6	80	11.91	12.32
2	6325		4.85	75	10.834	10.234
3	FH 2				10.205	10.765
4	FH 25				9.194	9.994
5	FH 26				9.654	10.654
6	FH 1				9.6222	10.212
7	FH 3				9.267	9.927
8	6312		5.3	1050	8.639	9.479
9	6326		4.53	100	8.118	9.208
10	6323 - 2		5.3	80	7.99	8.37
11	FH 4				8.978	9.478
12	FH 5				9.156	10.146
13	FH 6				8.96	9.75
14	FH vet				8.459	9.159
15	6327		5.75	100	8.255	9.045
16	FH 10				7.943	9.013
17	FH 7				7.928	8.818
18	FH 8				7.269	8.289
19	FH 9				7.218	8.158
20	FH 11				7.723	8.453
21	FH 15				6.517	7.207
22	FH 17				5.789	6.759
23	6314		6.2	1050	6.408	6.408
24	6323 - 3		4.7	80	7.168	7.835

blank spaces indicate information not available

Details of wells and bores incorporated in 1997 and 1998 surveys

SURFACE WATER QUALITY DATA FOR TAKAKA RIVER AND TRIBUATARIES

Analysed for Tasman District Council by Cawthron Institute (Nelson)

RIVER AND LOCATION	Sampling Date	Nitrate N g/m^3	Chloride Cl g/m^3	Calcium Ca g/m^3	Magnesium Mg g/m^3	Hardness $CaCO_3$ g/m^3	Ammonia g/m^3	Total nitrogen g/m^3	Suphate SO_4 g/m^3	Conductivity mS/m	Silica SiO_2 g/m^3	Alkanlinity $CaCO_3$ g/m^3	Bicarbonate HCO_3 g/m^3	pH	Free CO_2 g/m^3	Iron Fe g/m^3	Manganese Mn g/m^3	Sodium Na g/m^3	Potassium K g/m^3	Turbidity NTU	Sol Reactive P	Dissolved oxygen
Takaka @ Headwaters	19-Jun-92	10					15			8.3				7.9							1	102
Takaka @ Harwoods	19-Mar-86	0.008	2.4	10.1	2.4	35	<0.001	0.14	1.2	7		33		7.6	2.1	0.05	<0.01	2.1	0.3			
	5-Mar-87	0.006	2.6	13.8	2.74		<0.005		2.6	8		34		7.5	2.1			2.09	0.22		<0.001	9.5
	1989		2.1	13.9	2.8				2.7	8.9		37	46	8				2	0.17			
	21-Jun-91		1.8	12	2.5				3.5			39	48	7.3				2.3	0.26			
	19-Jun-92	27					85			7.1				7.8							<1	102
Takaka @ Lindsays Bridge	21-Jun-91		1.8	12.7	2.5				3.7			38	46	7.7				2.4	0.26			
Takaka @ Sparrows	21-Jun-91		2.3	12.3	2.5				3.3			44	54	7.2				2.3	0.27			
Takaka @ Craigieburn	5-Mar-87	0.012	3	15.7	2.74		0.012		2.3	8.8		37		7.5	2.3			2.23	0.26		<0.001	9.4
	19-Jun-92	35					84			7.5				7.9							1	103
Takaka @ Paynes Ford	1989		2.9	17.4	1.6				2.6	9.6		34	42	8				2.1	0.5			
	19-Jun-92	150					21														1	
Takaka @ Kotinga	19-Mar-86	0.13	2.3	12.7	1.9	39	<0.001	0.19	1.8	8.2		39		7.5	3	<0.05	<0.01	2.3	0.4			
	5-Mar-87	0.08	2.3	16.4	2.15		<0.005		2.2	8.7		37		7.3	2.8			2.41	0.32		<0.001	9.5
	19-Jun-92	84/62					<5/13			7.8				7.7							<1/1	103
Takaka @ Roses	19-Jun-92	99/84					12 73			7.2				7.8							<1/<1	102
Takaka @ Pages Cut	19-Mar-86	0.029	1.2	13.7	1.8	41	<0.001	0.035	<1.0	5.8		41		7.3	3.5	0.06	<0.01	2.3	0.4			
Takaka @ Waitapu Bridge	19-Jun-92	140/150					56/9														6	
MAJOR TRIBUTARY RIVERS																						
Anatoki @ Happy sams	5-Mar-87	0.032	2	27	1.77		<0.005		1.9	11.1		53		7.8	2.2			1.96	0.26		<0.001	10.2
Anatoki @ Bridge	21-Jun-91		1.5	20.6	1.7				3.2			53	65	7.9				2.2	0.33			
Anatoki @ Sawmill	21-Jun-91		1.5	21.5	1.7				3.4			55	67	7.7				2.4	0.33			
Anatoki @ Confluence	19-Jun-92	32					<5			7.5				8.9							1	105
Waingaro @ Hanging Rock	5-Mar-87	0.032	2.3	16.2	2.21		0.009		1.9	8.5		38		7.5	2.3			2.38	0.28		0.002	10.2
Waingaro @ Pettersons	21-Jun-91		3.6	16.1	2.3				3.4			44	54	7.2				3.7	0.58			
Waingaro @ Savages	21-Jun-91		2.8	15.4	1.8				4.1			48	59	7.2				3.4	0.41			
Waingaro @ Confluence	1989		3.2	11.9	2				2.4	8.4		35	42	7.7				2.8	0.31			
	5-Mar-87		2.8	15.4	2.2				3.7			44	54	7.3				3.3	0.44			
Waingaro	19-Jun-92	26					<5			8.8				8.3							<1	100
MINOR TRIBUTARY CREEKS																						
Craigieburn Ck	1989		1.2	9.8	0.98				2.6	5.8		25	26	9				1.5	0.17			
Ironstone Ck	1989		1.5	27.9	1				<1	14		61	75	7.5				2.5	0.29			
Rameka Ck	21-Jun-91		2.4	39	2				3.3			35	43	7.3				4.2	0.66			

WATER QUALITY DATA FOR MISCELLANEOUS SPRINGS

Analysed for Tasman District Council by Cawthron Institute (Nelson)

SPRING LOCATION AND ASSOCIATED ROCK TYPE	Sampling Date	Nitrate N g.m-3	Chloride Cl g.m-3	Calcium Ca g.m-3	Magnesium Mg g.m-3	Hardness $CaCO_3$ g.m-3	Ammonia g.m-3	Total nitrogen g.m-3	Suphate SO_4 g.m-3	Conductivity mS/m	Silica SiO_2 g.m-3	Alkalinity $CaCO_3$ g.m-3	Bicarbonate HCO_3 g.m-3	pH	Free CO_2 g.m-3	Iron Fe g.m-3	Manganese Mn g.m-3	Sodium Na g.m-3	Potassium K g.m-3	Turbidity NTU	Sol Reactive P	Dissolved oxygen
Spittals Spring (Arthur Ma)	1989		1.6	36	1.4				1.1	13		71	86	7.6				1.9	0.33			
	21-Jun-91	0.29	1.2	42	1.9				2			120	150	7.8				3	0.54			
	31-Oct-94	0.072	2.1	40	1.5	106	<0.005	0.47	2.3	22	8.9	110	133	7.6	3	<0.05	<0.01	2.4	0.4		0.01	
Fish Creek (Arthur Ma)	21-Jun-91	0.32	17	41	3.5				14			110	130	7.4				13	1.7			
	31-Oct-94	0.2	25	45	3.8	128	<0.005	0.38	5.7	34	5.4	137	167	7.5	8.1	<0.05	<0.01	17	1.9		0.004	
Springbrook (Arthur Ma)	31-Oct-94	0.076	5.3	29	2.4	82	<0.005	0.46	1.9	18	4.8	85	104	7.5	4.2	<0.05	<0.01	<0.05	0.5		0.005	
East Takaka (Tak Lmst)	21-Jun-91	1.8	3.4	25.5	2.4				7			64	78	7.6				3.3	0.93			
	31-Oct-94	0.42	3.2	43	2.3	117	0.058	0.77	3.8	2.3	4.9	116	142	8.2	1.9	<0.05	<0.01	3.5	0.4		0.008	

APPENDIX H-I Summary of surface water quality data

Table 13.6 **Guideline Values for aesthetic determinands**

Determinand	Guideline Value	Units	Comments
Aggressiveness	LSI > 0		Corrosion
Aluminium	0.15	mg/L	Depositions, discoloration.
Ammonia	1.5	mg/L	Odour and taste
Calcium: see hardness		mg/L	
Chloride	250	mg/L	Taste, corrosion
Chlorophenols 2-chlorophenol 2,4-dichlorophenol 2,4,6-trichloro-phenol	 0.0001 0.0003 0.002	mg/L	 Taste Taste Taste
Colour	10	TCU	Appearance
Copper	1	mg/L	Staining of laundry and sanitary ware (health based provisional guideline value 2 mg/L)
Ethylbenzene	0.002	mg/L	For odour and taste (health based guideline value 0.3 mg/L)
Hardness (total) (Ca + Mg)	200	mg/L	High hardness causes scale deposition, scum formation; low hardness: possibly causes corrosion
Hydrogen sulphide	0.05	mg/L	Odour and taste
Iron	0.2	mg/L	Staining of laundry and sanitary ware
Magnesium (see hardness)		mg/L	
Manganese	0.05	mg/L	Staining of laundry and sanitary ware
Odour	should be acceptable to most consumers		
pH	6.5-8.5		Should be between 7.0 and 8.0. Low pH: corrosion; high pH: taste, soapy feel. Preferably pH<8 for effective disinfection with chlorine
Sodium	200	mg/L	Taste
Styrene	0.004	mg/L	For odour and taste (health based guideline value 0.03 mg/L)
Sulphate	250	mg/L	Taste, corrosion
Taste	should be acceptable to most consumers		
Temperature	should be acceptable to most consumers		
Toluene	0.024	mg/L	Odour and taste (health based guideline value 0.8 mg/L)
Total dissolved solids	1000	mg/L	Taste
Turbidity	2.5	NTU	Appearance, for effective terminal disinfection, median turbidity < 1 NTU, single sample < 5 NTU
Xylene	0.02	mg/L	Odour and taste (health based guideline value 0.6 mg/L)
Zinc	3	mg/L	Appearance, taste

APPENDIX H-II Excerpts from the New Zealand Drinking Water Standards

TABLES OF MAVS

MAVs for micro-organisms of health significance

MICROORGANISM	MAV
Faecal coliform	Must not be detectable in 100 mL of sample
Viruses	No enteric viruses shall be detectable in 100L of sample.
Protozoa (pathogenic)	Not detectable in 100L sample.
Helminths (pathogenic)	Not detectable in 100L sample.
Algae	No toxic algae present in 10mL of sample

MAVs for inorganic determinands of health significance

NAME	MAV	UNITS	REMARKS
Aluminium			NAD
Antimony	0.003	mg/L	
Arsenic	0.01	mg/L	For excess lifetime skin cancer risk of 6 x 10^{-4} P, for practical quantitative analysis
Asbestos			NAD
Barium	0.7	mg/L	
Beryllium			NAD
Boron	0.3	mg/L	
Bromate	0.025	mg/L	For excess lifetime cancer risk of 7 x 10^{-5}
Cadmium	0.003	mg/L	
Chlorate			NAD
Chlorine (free)	5	mg/L as Cl_2	ATO
Chlorite	0.3	mg/L as ClO_2	P, disinfection must never be compromised
Chromium	0.05	mg/L	P, limited information on health effects
Copper	2	mg/L	ATO
Cyanide (total)	0.08	mg/L	
Cyanogen chloride (as CN)	0.08	mg/L	
Dichloramine			NAD
Fluoride *	1.5	mg/L	
Iodine			NAD
Lead	0.01	mg/L	
Manganese	0.5	mg/L	ATO
Mercury (total)	0.002	mg/L	
Molybdenum	0.07	mg/L	
Monochloramine	3	mg/L	
Nickel	0.02	mg/L	
Nitrate	50	mg/L expressed as NO_3	The sum of the ratio of the concentrations of nitrate and nitrite to each of their respective MAVs should not exceed 1
Nitrite	3	mg/L expressed as NO_2	The sum of the ratio of the concentrations of nitrate and nitrite to each of their respective MAVs should not exceed 1. P, limited information on health effects
Potassium permanganate			NAD
Selenium	0.01	mg/L	
Silver			U
Sodium			NAD
Tin			U
Trichloramine			NAD
Uranium			NAD

* The fluoride content recommended for drinking-water by the Public Health Commission for oral health reasons is 0.7 - 1.0 mg/L.

Abbreviations:
- P - Provisional MAV.
- NAD - No adequate data to permit recommendation of a health-based MAV.
- ATO - Concentrations of the substance at or below the health-based MAV may affect the appearance, taste or odour of the water.
- U - Unnecessary to recommend health-based MAV because they are not hazardous to human health at concentrations normally found in drinking water.

Tables derived from NZWS guidelines (Ministry of Health 1995)

APPENDIX H-III Summary of groundwater quality data

GROUNDWATER QUALITY DATA FOR TAKAKA TOWNSHIP GRAVEL AQUIFER AND SURROUNDS -

Analysed for Tasman District Council by the Cawthron Institute (Nelson). All samples collected 13 March 1996.

SITE NUMBER	WWD LOCATION	GRID REFERENCE	Conductivity mS/m Temp 25 C	Temp	Nitrate N g/m^3	Chloride Cl g/m^3	Calcium Ca g/m^3	Magnesium Mg g/m^3	Hardness $CaCO_3$ g/m^3	Nitrite g/m^3	Ammonia g/m^3	Total nitrogen g/m^3	Suphate SO_4 g/m^3	Conductivity mS/m	Silica SiO_2 g/m^3	Alkanlinity $CaCO_3$ g/m^3	Bicarbonate HCO_3 g/m^3	pH	Free CO2 g/m^3	Total P g/m^3	Soluble reactive P g/m^3	Iron Fe g/m^3	Manganese Mn g/m^3	Sodium Na g/m^3	Potassium K g/m^3	Total DS g/m^3	Fixed DS g/m^3	Organic DS g/m^3	Cation Anion g/m^3	Turbidity NTU
1	WWD 6305	N25 940339	13	14.2	1.6	5.2	16	2.3	49																					
2	WWD 6307	N26 945390	10.8	12.8	0.48	3.3	14	2.1	44	<0.001	<0.005	1.7	3.4	11	5.2	43	52	7.0	7	0.02	0.005	<0.05	<0.01	3.1	0.4	60	42	18	0.99	0.2
3	WWD 6308	N26 943392	12.2	13.5	1.2	4.6	16	2.4	50																					
4	WWD 6310	N26 951389	18.2	14	1.6	5.8	23	2.9	70																					
5	WWD 6311	N26 936384	10.8	15	0.46	2.4	15	2.2	47	<0.001	<0.005	1.7	2.8	11	5.5	50	61	7.7	2.9	0.019	0.002	<0.05	<0.01	2.7	0.51	24	21	3	0.94	
6	WWD 6312	N26 931390	11.3	14.3	1.1	3.8	15	1.8	45																					
7	WWD 6314	N25 936400	12	14.9	2	4.5	14	2.2	44	<0.001	<0.005	2.8	7.8	12	7.5	35	43	6.3	17	0.022	0.006	0.07	<0.01	4	0.96	60	48	12	1.06	
8	WWD 6324	N26 944382	29.8	14.8	3.1	9.5	42	2.8	118																					
9	WWD 6325	N26 937383	12.7	15.9	1.1	4	17	2.5	52																					
10	WWD 6326	N26 941388	12.8	13.8	0.7	3.3	18	2.5	55	<0.001	0.009	2	4.6	13	5.5	48	59	6.3	18	0.021	0.001	0.08	<0.01	3.7	0.58	70	60	10	1.1	
11	WWD 6327	N26 941394	12.7	13.7	1.4	4.4	17	2.3	52	<0.001	<0.005	2.3	6.6	13	6.4	43	52	6.6	13	0.021	0.002	0.65	0.01	3.7	1.2	75	47	28	1.08	
12	WWD 6328	N26 936388	11.6	14.8	1.4	3.2	16	2.1	49	<0.001	<0.005	1.7	5.6	11	5.5	44	54	6.4	15	0.02	0.001	0.05	<0.01	3	0.74	85	41	44	1.01	
13	WWD 6329	N26 937396	12	15.3	1.2	4.7	15	2.2	47	<0.001	<0.005	2.6	7.3	12	7.4	36	44	6.1	20	0.022	0.006	0.11	<0.01	3.8	0.98	70	55	15	1.1	
14	WWD 6005	N25 933405	12.8	15	2.3	6.8	15	2.4	47																					
15	WWD 6009	N25 932412	12.7	15.3	0.82	6.2	13	2.6	44																					
16	WWD 6101	N25 945404	13.4	16	2.5	5	17	2.3	52																					
17	WWD 6401	N26 957391	26.3	14.8	6.8	16	31	3.8	94	<0.001	<0.005	8.6	15	26	9.9	61	74	6.4	15	0.018	0.002	<0..05	0.02	6.7	7.7	160	100	60	1.12	
18	WWD 6402	N25 956397	28.2	14.3	3.3	11	41	3.4	116																					
19	WWD 6611	N26 947377	21	15.1	1.9	5	35	2.3	98																					

GROUNDWATER QUALITY DATA FOR EAST TAKAKA GRAVEL AQUIFER -

Analysed for Tasman District Council by Cawthron Institute (Nelson). All samples were collected 13 March 1996.

SITE NUMBER	WWD LOCATION	GRID REFERENCE	Conductivity mS/m Temp 25 C	Temp	Nitrate N g/m^3	Chloride Cl g/m^3	Calcium Ca g/m^3	Magnesium Mg g/m^3	Hardness $CaCO_3$ g/m^3	Nitrite g/m^3	Ammonia g/m^3	Total nitrogen g/m^3	Suphate SO_4 g/m^3	Conductivity mS/m	Silica SiO_2 g/m^3	Alkanlinity $CaCO_3$ g/m^3	Bicarbonate HCO_3 g/m^3	pH	Free CO2 g/m^3	Total P g/m^3	Soluble reactive P g/m^3	Iron Fe g/m^3	Manganese Mn g/m^3	Sodium Na g/m^3	Potassium K g/m^3	Total DS g/m^3	Fixed DS g/m^3	Organic DS g/m^3	Cation Anion g/m^3	Turbidity NTU
31	WWD 6804	N26 952335	25	14.4	2.9	4.9	15	1.7	44																					
32	WWD 6816	N26 950332	14.6	14.5	2	4.7	21	1.8	59																					
33	WWD 6819	N26 949319	18	14.3	1.7	4.5	29	2.2	80																					
34	WWD 6820	N26 951316	20.1	15.3	1.6	5	34	2	93																					
35	WWD 6824	N26 953344	23.9	13.4	1.5	4.1	41	2.1	111																					

GROUNDWATER QUALITY DATA FOR WAIKOROPUPU SPRINGS *-Analysed for Tasman District Council by the Institute of Geological and Nuclear Sciences (Wairakei)*

Date sampled	pH	Conductivity mS/m	Alkalinity g/m^3	Chloride g/m^3 Cl	Sulphate g/m^3 SO_4	Silica g/m^3 SiO_2	Nitrate g/m^3 NO_3	Nitrite-Nitrogen g/m^3 NO_2-N	Nitrate-Nitrogen g/m^3 NO_3-N	Ammonical Nitrogen g/m^3 NH_4-N	DRP g/m^3	Sodium g/m^3 Na	Potassium g/m^3 K	Calcium g/m^3 Ca	Magnesium g/m^3 Mg	Iron g/m^3 Fe	Manganese g/m^3 Mn	Bromide g/m^3 Br	Fluoride g/m^3 F	TDS g/m^3	Cations moles/L	Anions moles/L	Ion Balance
26-Sep-90	7.5	72	224	104.7	18.5	6.3			0.3			65	4.7	54.6	8.8	<0.1	<0.05						
28-Nov-90	7.5	77	229	121	20.2	7.5			0.2			75.7	5.3	73.4	9.6	<0.1	<0.07						
27-Mar-91	7.7	60	196	80.9	15.3	6.7			0.43			56.2	4.2	65.8	7.1	0.1	<0.04						
20-Jun-91	7.7	53	185	58	13.6	6.3			0.15			41.4	3.7	59.7	6.4	<0.1	<0.06						
23-Sep-91	7.6	70	215	101	19	6.9			0.17			66.9	5.2	68.2	8.5	<0.1	<0.08						
3-Dec-91	7.6	63	198	86.5	14.3	6.6			0.13			54.1	4.6	60.5	7.6	<0.1	<0.05						
24-Mar-92	7.7	60	194	83.1	14.4	6.8			0.12			55	4.3	63	7.1	0.1	<0.06						
13-Jul-92	7.7	64	201	89.1	13.3	6.6			0.12			58.7	4.8	61.9	3	<0.2	<0.09						
15-Sep-92	7.6	65	204	82.4	13.4	7.1			0.12			58.7	4.7	66.4	7.6	<0.1	<0.06						
2-Dec-92	7.8	66	211	96	17	6.6			0.38			58	4.7	65	7.9	0.04	<0.02						
2-Mar-93	7.7	64	212	93	18	4			0.34			56	4.5	60	7.7	<0.04	<0.02						
21-Jun-93	7.6	69	215	108	19	6.6			0.33			65	4.9	65	8.6	<0.04	<0.02						
26-Aug-93	7.6	70	207	96	18	7			0.39			60	4.2	64	8.9	<0.04	<0.02						
13-Dec-93	7.7	67	205	98	17	6.6			0.33			60	4.5	61	8.3	<0.04	<0.02			461	0.00645	0.0065	0.99
23-Mar-94	7.7	63	205	93	17	6.6			0.33			57	4.6	62	8.1	<.04	<.02			454	0.00636	0.00636	1
7-Jun-94	7.7	61	200	98.2	14.6	6.3			0.409			55	4.7	63.5	7.5	<.2				450	0.0063	0.00638	0.99
20-Sep-94	7.6	67	199	102	16	6			0.333			59	5.3	64	8.6	<.2				460	0.0066	0.00648	1.02
16-Jan-95	7.7	58	188	80	16.1	6.4			0.331			45.1	4.1	60.2	6.7	<.2				407	0.00562	0.00569	0.99
20-Mar-95	7.7	65	197	99.7	18.4	6.1			0.36			62	6.1	61.1	9.1	<.2				460	0.006651	0.006446	1.03
21-Jun-95	7.7	68	202	106.7	14.4	6.8			0.35			65.5	5.4	62.9	9.3	<.1				473	0.006892	0.006639	1.04
3-Oct-95	7.7	70	203	112.7	17.2	6.9			0.37			67	2.2	63.6	9.5	0.04				483	0.006927	0.006891	1.01
5-Dec-95	7.8	66	196	107.4	17.6	6.5			0.37			61	4.7	61.4	8.9	0.01				464	0.00657	0.006637	0.99
6-Mar-96	7.7	67	206	111.6	18.9	6.6	0.31	<0.002	1.37	0.02	<0.004	63.5	5.7	63.2	9.6	0.02				486.5	0.007	0.007	0.99
5-Jun-96	7.7	65	187	106.2	16.4	6.4	0.902	<0.005	4	<0.01	0.01	59	4.7	67	8.7	<0.05	<0.05	0.33	<0.05	475.3	0.0075	0.006	1.04
4-Sep-96	8	65	203	103.8	17.2	6.8	0.381	<0.005	1.6866	0.005		63	4.7	64.9	8.8	<0.01	<0.01	0.33	<0.05	474.2			1.03
17-Dec-96	7.6	0.67	200	100	16.69	5.795	0.36		1.5936	<0.01		61	4.5	63.2	8.36	<0.01	<0.01	0.32					1.02
19-Mar-97	8.4	0.36	183	45	10.4	5.985	0.33		1.4608	<0.01		32.2	3	51.4	5.22	<0.01	<0.01	0.144	0.03				0.99
17-Jun-97	7.6	0.58	206	69	14.1	6.2	0.31		1.37	0.02		47	4.5	61	6.9	0	0	0.22					1.02
23-Sep-97	8.2	0.62	217	80	15.6	6.5	0.32		1.42	<0.01		51	4.6	64.3	7.4	<0.01	<0.01	0.24					1

GROUNDWATER QUALITY DATA FOR THE ETML AQUIFER AT WWD 6601 - *Analysed for the Tasman District Council by the Institute for Geological and Nuclear Sciences Ltd (Wairakei)*

Date sampled	pH	Conductivity mS/m	Alkalinity g/m^3	Chloride g/m^3 Cl	Sulphate g/m^3 SO_4	Silica g/m^3 SiO_2	Nitrate g/m^3 NO_3	Nitrite-Nitrogen g/m^3 NO_2-N	Nitrate-Nitrogen g/m^3 NO_3-N	Ammonical Nitrogen g/m^3 NH_4-N	DRP g/m^3	Sodium g/m^3 Na	Potassium g/m^3 K	Calcium g/m^3 Ca	Magnesium g/m^3 Mg	Iron g/m^3 Fe	Manganese g/m^3 Mn	Bromide g/m^3 Br	Fluoride g/m^3 F	TDS g/m^3	Cations moles/L	Anions moles/L	Ion Balance
26-Sep-90	7.5	24	124	5.5	3.7	9.4			2.20			5.0	0.8	40.0	2.6	0.20	<0.05						
28-Nov-90	7.6	22.1	111	4.8	2.2	11.2			2.30			4.3	0.5	37.4	2.4	0.40	<0.07						
27-Mar-91	7.9	25.5	135	5.2	2.7	10.4			2.20			4.7	0.6	42.3	2.6	0.10	<0.04						
20-Jun-91	7.8	27	139	5.6	3.6	10.5			2.20			4.9	0.6	49.9	2.8	0.40	<0.06						
23-Sep-91	7.5	23.2	120	5.9	4.0	11.0			2.40			4.3	0.7	40.5	2.8	2.10	0.12						
3-Dec-91	7.7	25.3	132	5.3	3.6	10.5			2.30			4.7	0.6	44.0	2.6	<0.1	<0.05						
24-Mar-92	7.6	25.2	133	5.5	3.4	11.6			1.70			4.7	0.8	42.8	2.8	1.50	<0.06						
13-Jul-92	7.7	25.4	137	5.1	2.9	10.2			2.10			4.8	0.9	45.9	2.9	0.60	<0.09						
15-Sep-92	7.5	22.6	116	4.8	2.6	11.3			1.70			4.5	0.6	38.3	2.4	0.20	<0.06						
2-Dec-92	7.7	23	122	7.0	4.0	11.0			2.30			4.8	0.7	39.0	2.5	0.10	0.02						
2-Mar-93	7.7	26	151	6.0	6.0	8.0			1.79			4.8	0.8	43.0	2.7	1.34	0.05						
21-Jun-93	7.5	23	124	7.0	3.0	9.0			2.20			4.7	0.6	38.0	2.5	0.35	<0.02						
26-Aug-93	7.4	25	127	5.0	4.0	11.0			2.50			4.7	0.7	37.0	2.7	0.19	<0.02						
13-Dec-93	7.4	25	132	4.0	5.0	11.0		<0.002	1.92			4.6	0.7	41.0	2.8	0.88	0.02			204	0.00253	0.00251	1.01
23-Mar-94	7.5	26	154	6.0	5.0	14.0		<0.002	2.10			4.9	0.9	47.0	3.1	1.71	0.04			238	0.00290	0.00294	0.99
7-Jun-94	7.5	27	143	8.0	4.6	10.2		<0.002	1.99			5.0	1.1	45.2	3.3	<.2				223	0.00277	0.00281	0.99
20-Sep-94	7.3	26	133	7.3	4.7	8.4		0.007	2.21			4.9	0.9	46.8	2.9	<.2				212	0.00281	0.00265	1.06
16-Jan-95	7.7	27	142	7.2	4.0	10.1		0.009	2.29			5.0	1.0	48.0	2.8	<.2				222	0.00287	0.00277	1.04
20-Mar-95	7.5	24	110	13.5	2.9	9.9		0.013	4.04			4.9	1.0	39.1	2.7	<.2				188	0.00241	0.00254	0.95
21-Jun-95	7.6	24	131	7.0	4.2	10.4		0.002	2.02			4.8	0.9	43.1	2.9	<.1				207	0.00262	0.00258	1.02
3-Oct-95	7.3	22	114	8.1	3.2	11.4		0.029	2.40			4.6	0.8	38.8	2.5	0.05				186	0.00236	0.00234	1.01
5-Dec-95	7.6	24	132	6.7	4.0	10.1		0.011	2.11			4.8	0.9	44.4	2.9	0.03				208	0.00469	0.00259	1.04
6-Mar-96	7.3	25	143	6.6	4.6	9.5	1.70	0.002	7.53	0.03	0.01	5.2	1.7	45.8	3.1	0.04				227	0.00300	0.00300	1.02
5-Jun-96	7.2	25	137	6.6	4.0	10.0	2.12	<0.005	9.40	<0.01	0.01	4.8	0.9	41.9	3.1	<0.05	<0.05	<0.05	0.05	202	0.00260	0.00200	0.97
4-Sep-96	7.4	23	124.1	6.36	4.8	10.6	2.24	<0.005	9.916	0.004		4.7	0.73	42.1	2.6	0.01	<0.01	<0.05	<0.05	205.9			1.03
17-Dec-96	7.1	0.26	130	5.8	3.88	9.405	2.02		8.9521	<0.01		5.1	0.78	44.3	2.66	0.01	<0.01	0.04	0.05				1.06
19-Mar-97	8.2	0.22	151	6.1	3.8	10.26	2.4		10.6243	<0.01		5.2	0.66	46	2.85	0.01	<0.01	0.034	0.04				0.96
17-Jun-97	7.3	0.28	149	6.2	4	9.5	2.2		9.74	<0.02		5.2	0.76	50	3	0.01	0	0.04	0.04				1.05
23-Sep-97	8	0.26	138	6.1	3.7	10.4	2.3		10.18	0.01		4.8	0.76	44.4	2.8	0.16	<0.01	<0.05	<0.05				1

APPENDIX H-IV Sodium Adsorption Ratio data

Sodium Adsorption Ratio (SAR)

Ion concentration expressed in meq/l

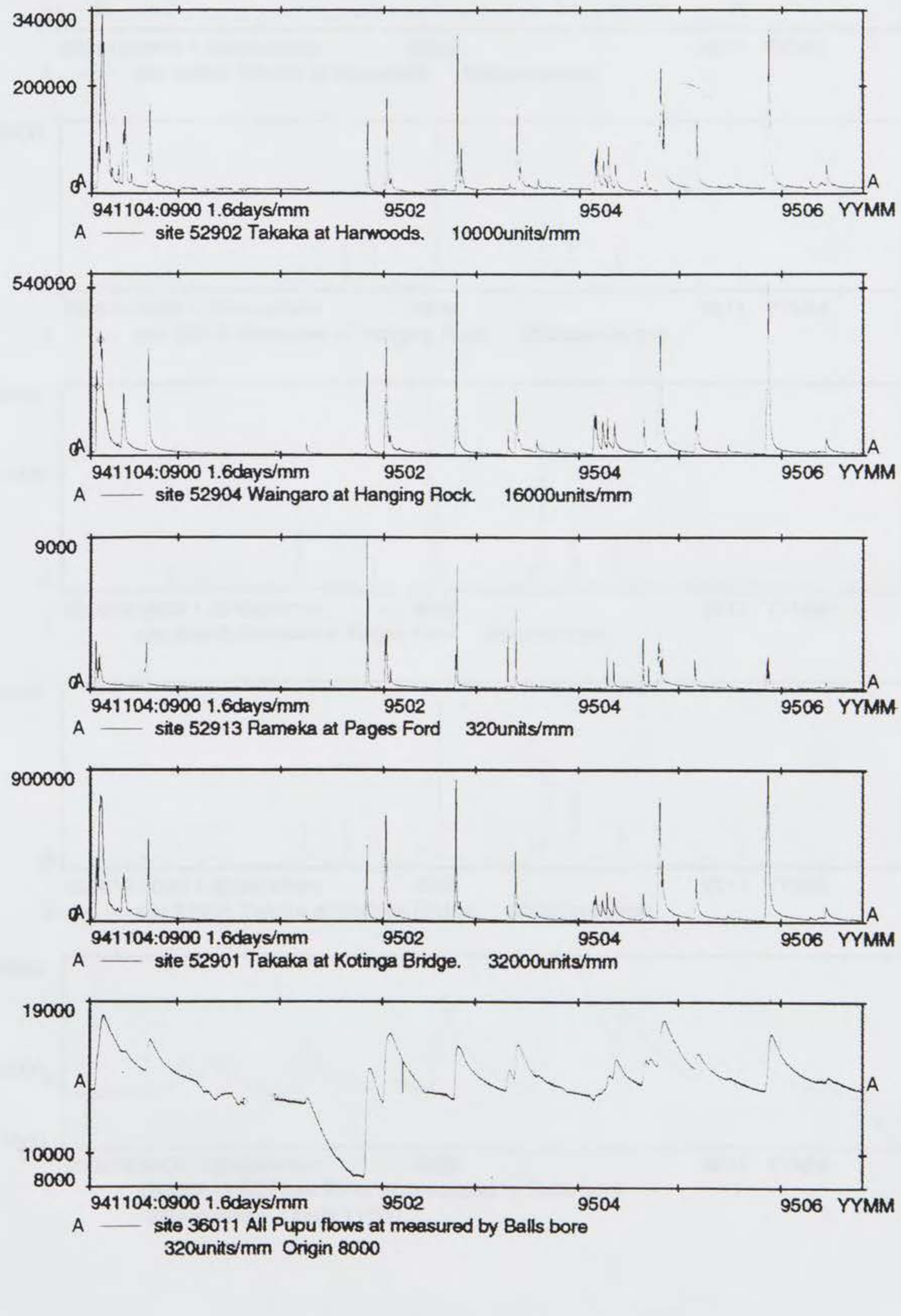
$$\frac{Na^{+}}{\sqrt{\frac{Ca^{2+} + Mg^{2+}}{2}}}$$

SAR measures the degree to which sodium in irrigation water replaces the adsorbed Ca^{2+} and Mg^{2+} in soil clays, and thus damages the soil structure. Irrigation water is usually classified in terms of salinity hazard (conductivity or total dissolved solids) and sodium hazard.

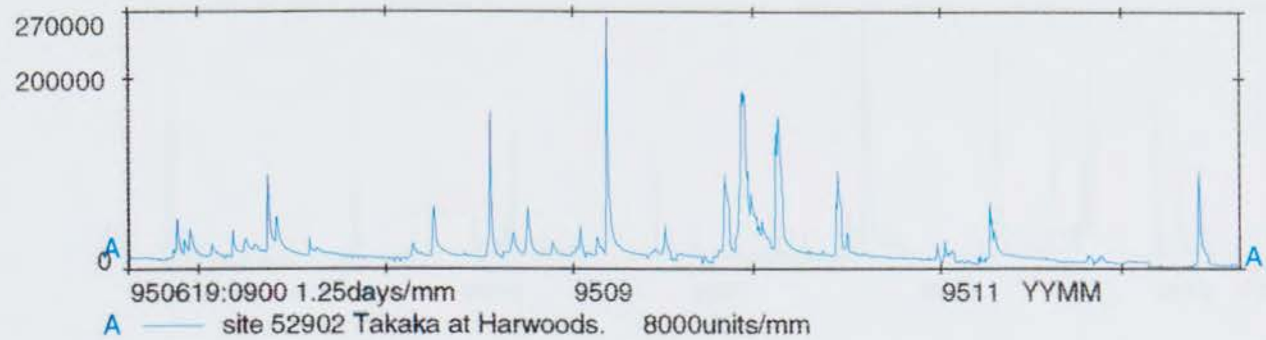
The following table presents SAR ratios for TTG and ETML Aquifers in 1996.

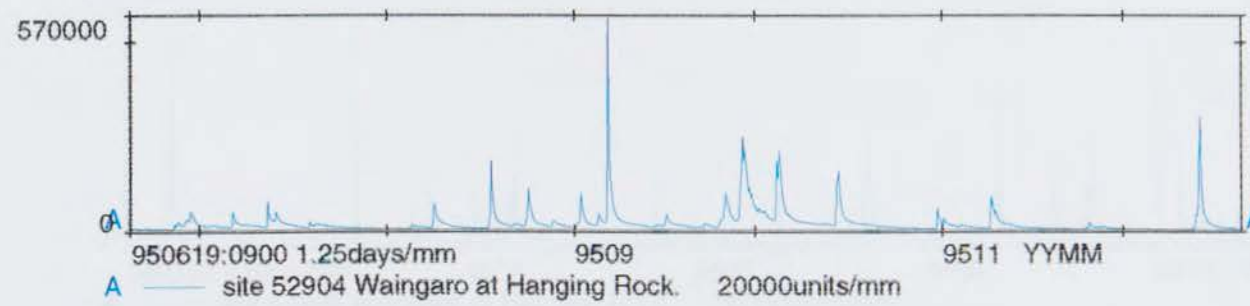
Site	Conductivity	SAR
2	11	0.20
5	11	0.17
7	12	0.26
10	13	0.21
11	13	0.22
12	12	0.19
13	12	0.24
17	26	0.30
ETML(mean)	26	0.19

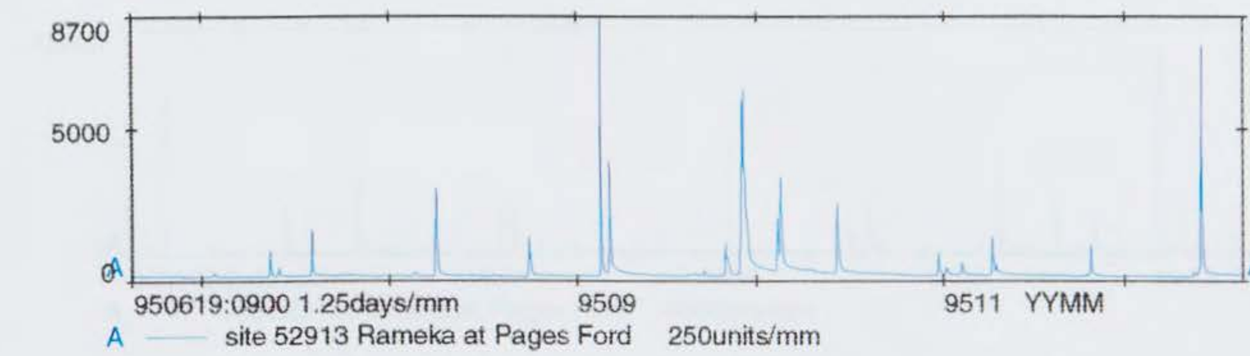
APPENDIX I WAM water balance

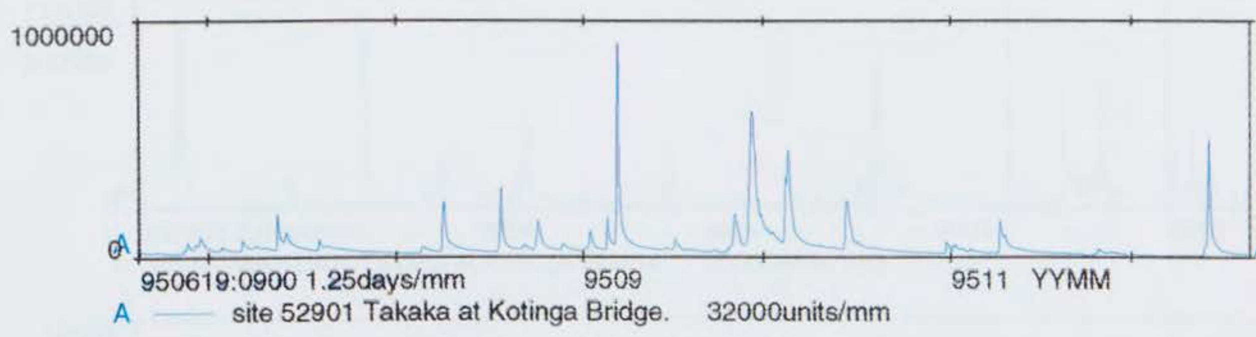


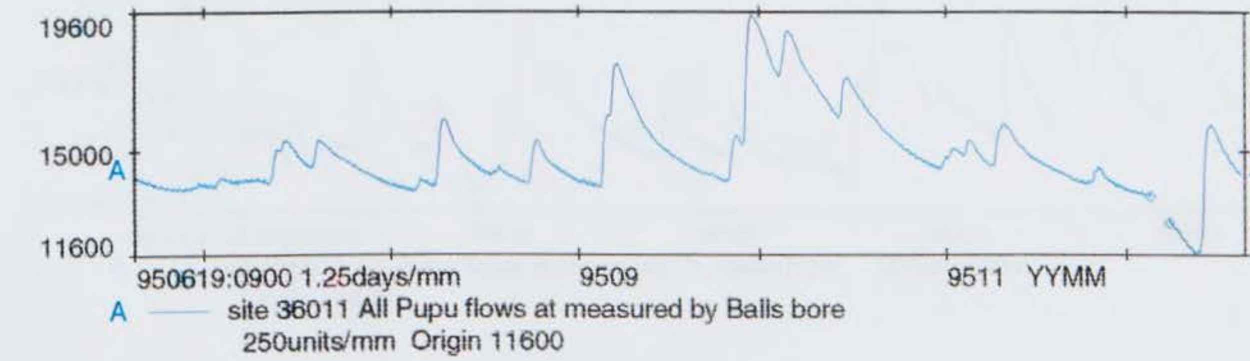
Data set A used in method two of the WAM Aquifer water balance



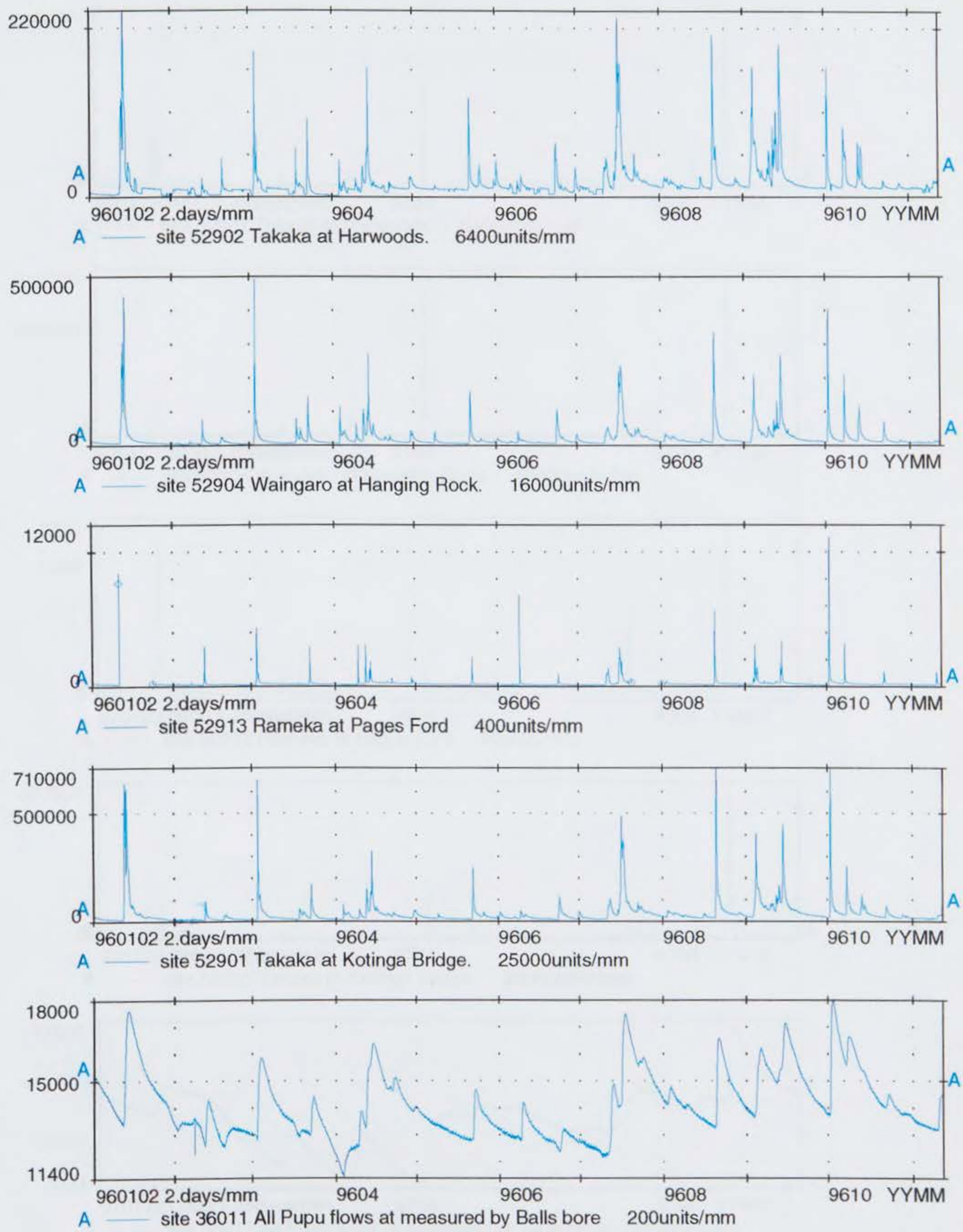




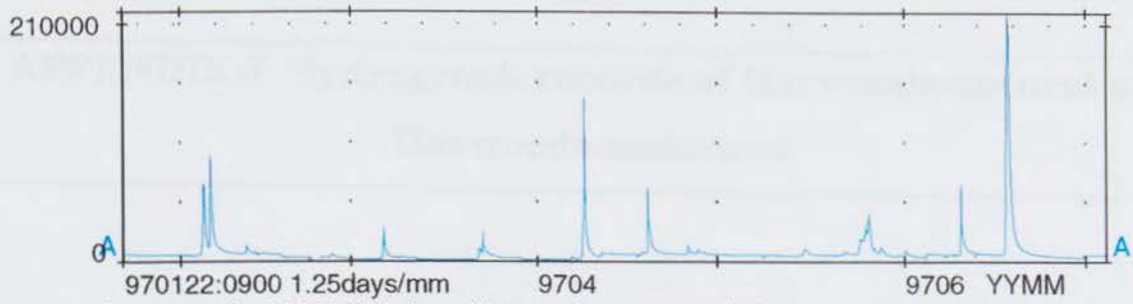




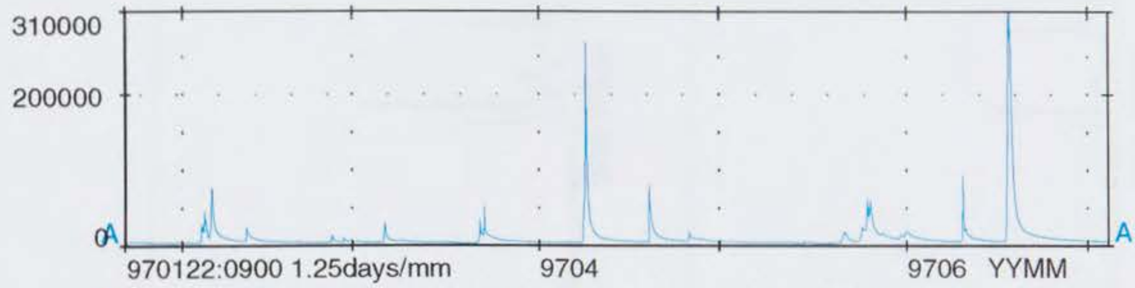
Data Set B used in method two of the WAM Aquifer water balance



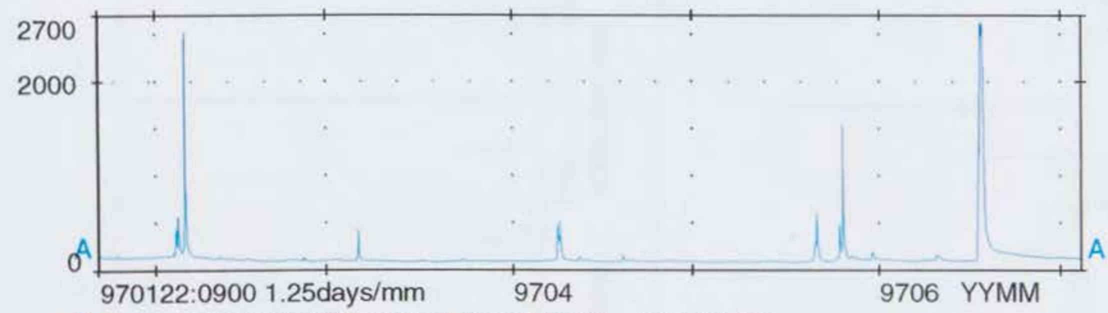
Data Set C used in method two of the WAM Aquifer water balance



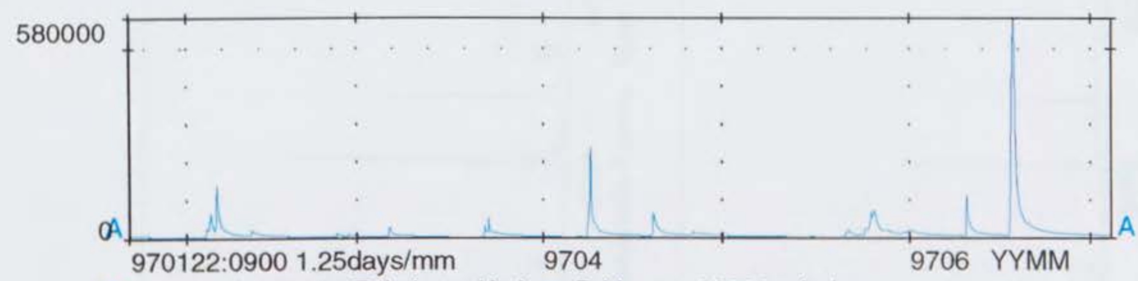
A —— site 52902 Takaka at Harwoods. 6400units/mm



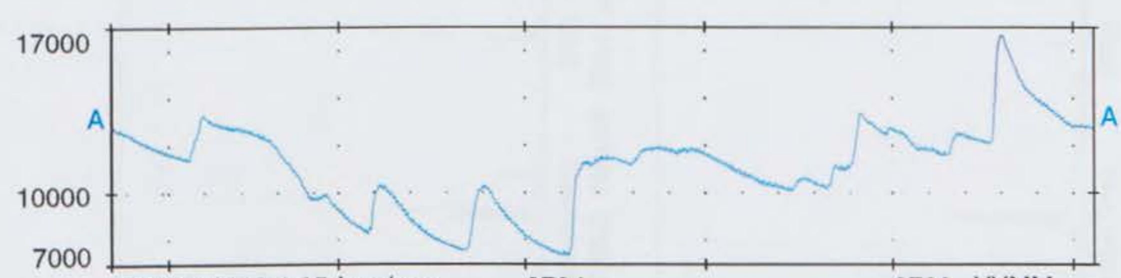
A —— site 52904 Waingaro at Hanging Rock. 10000units/mm



A —— site 52913 Rameka at Pages Ford 80units/mm



A —— site 52901 Takaka at Kotinga Bridge. 20000units/mm

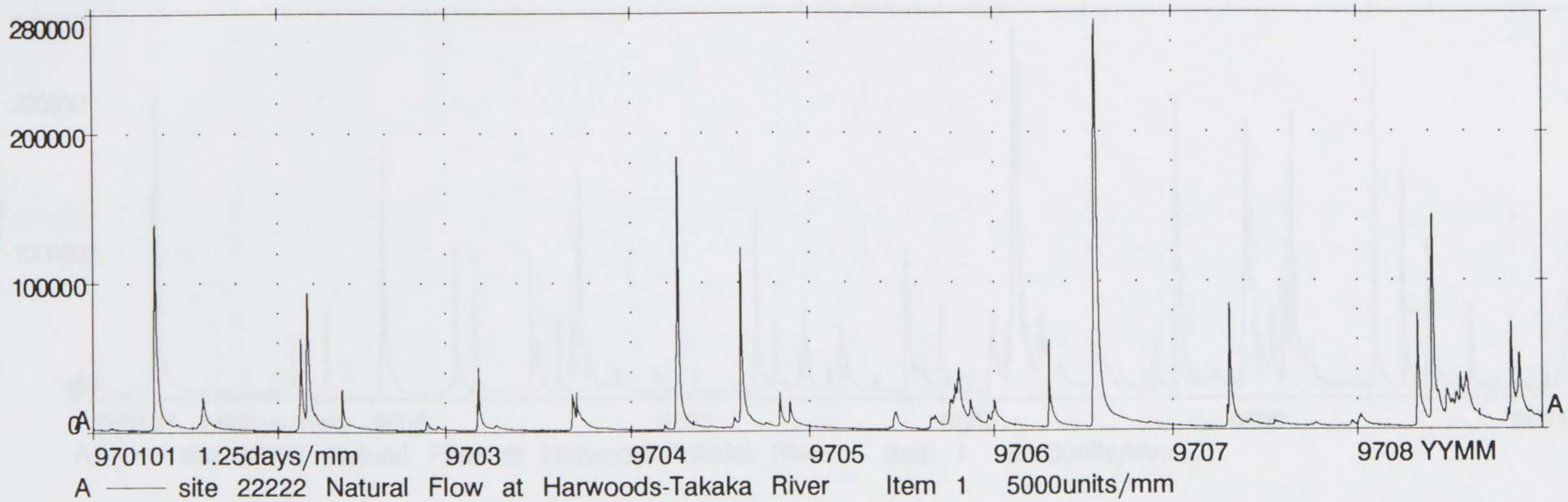


A —— site 36011 All Pupu flows at measured by Balls bore 320units/mm
Origin 7000

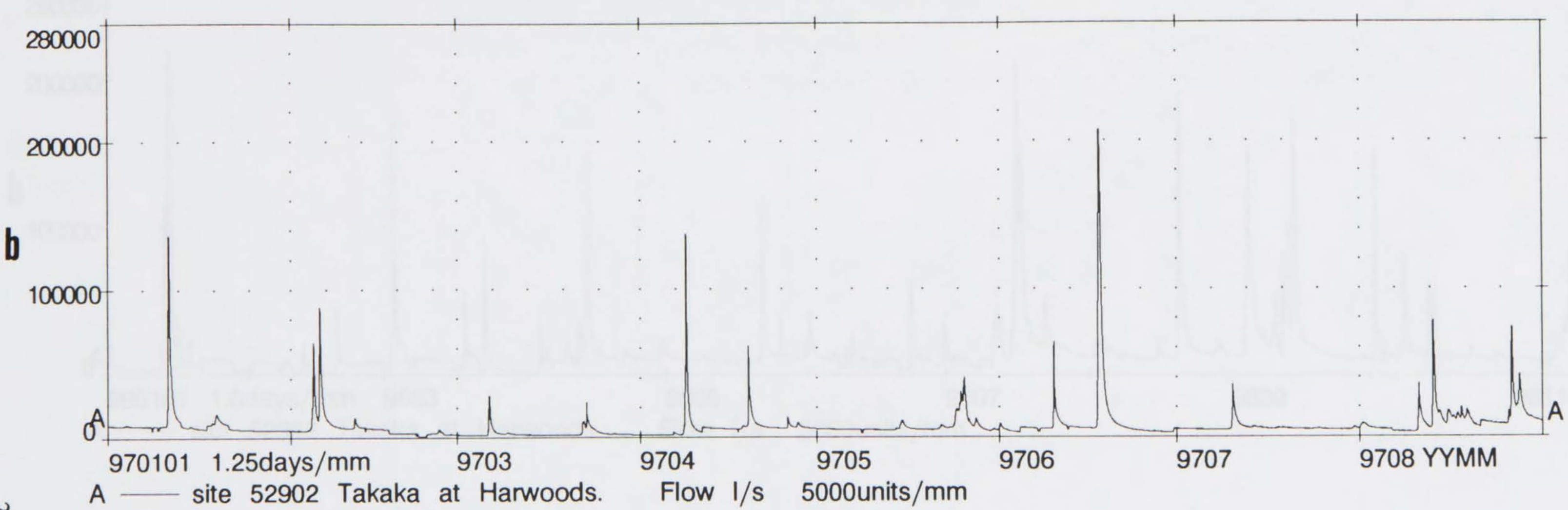
Data Set D used in method two of the WAM Aquifer water balance

APPENDIX J Hydrograph records of Harwoods-natural and Harwoods-measured

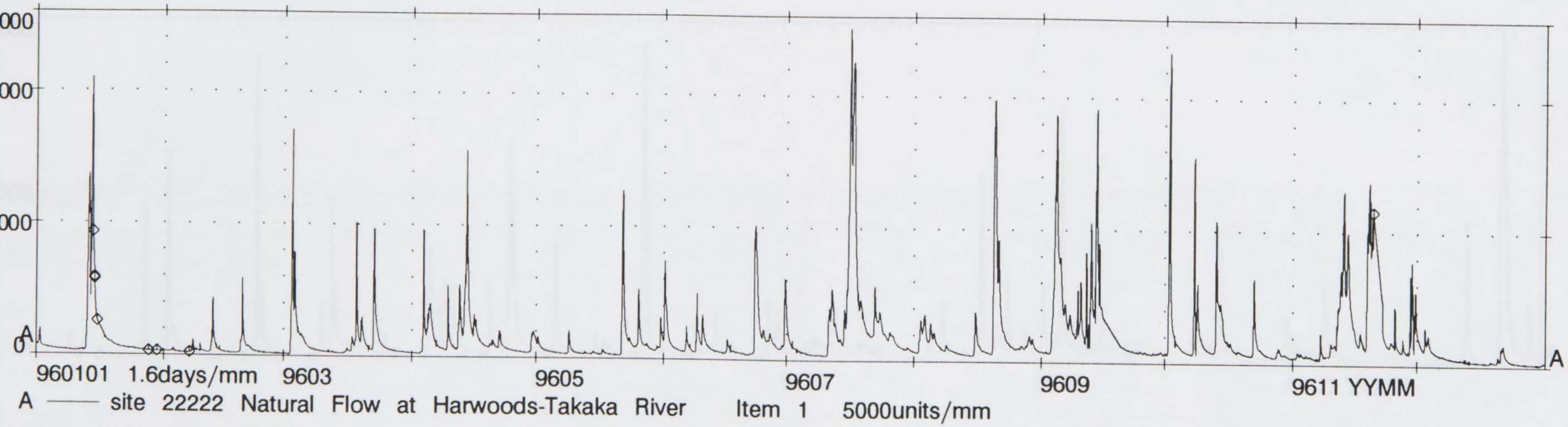
a



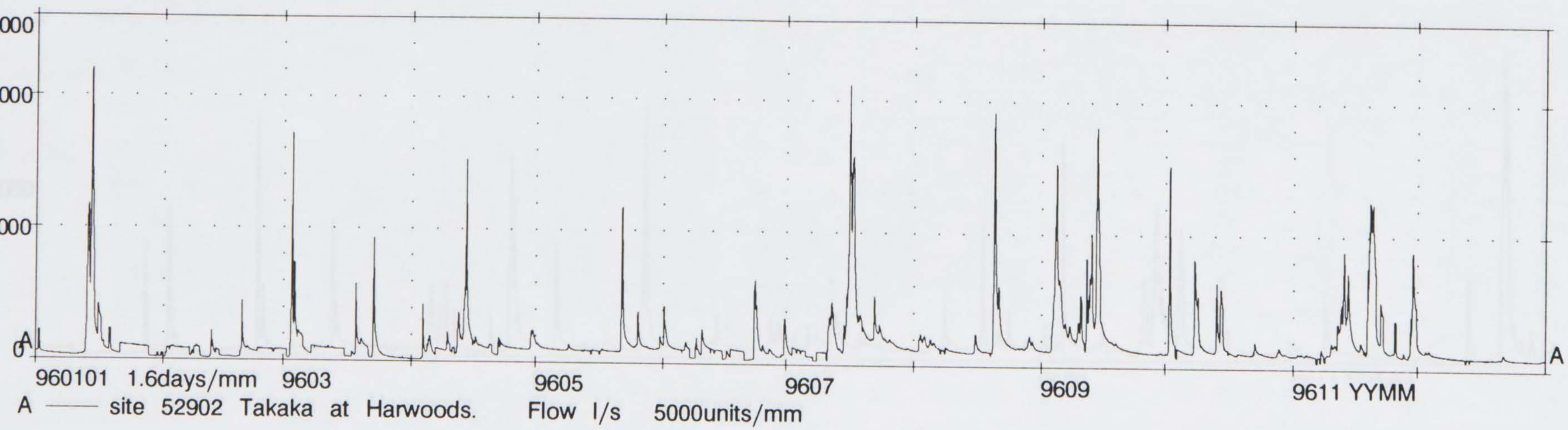
b



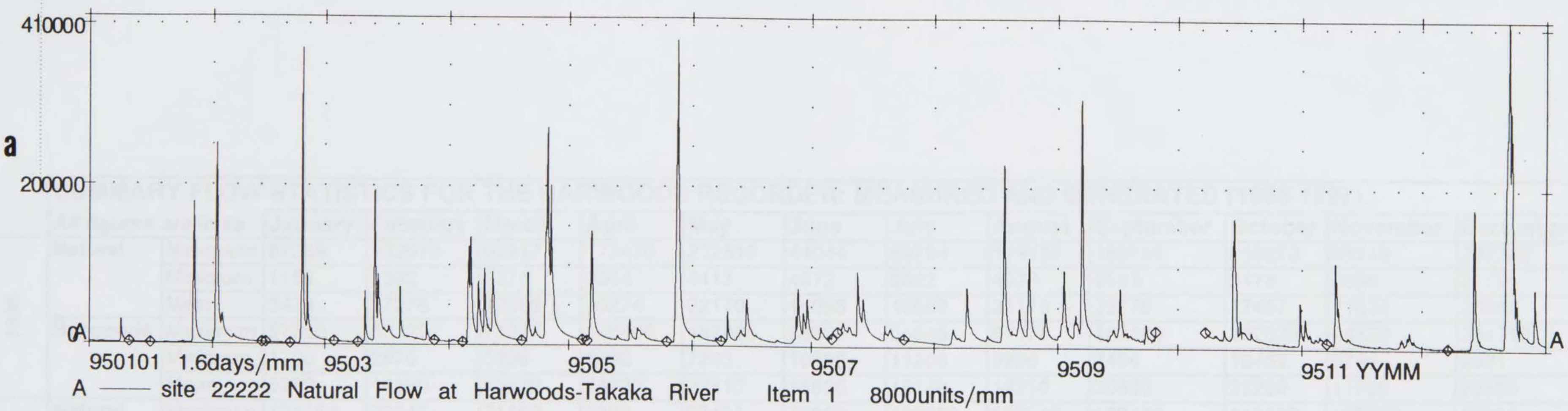
a


260000
200000
100000
0
A
960101 1.6days/mm 9603
9605
9607
9609
9611 YYMM
A —— site 22222 Natural Flow at Harwoods-Takaka River Item 1 5000units/mm

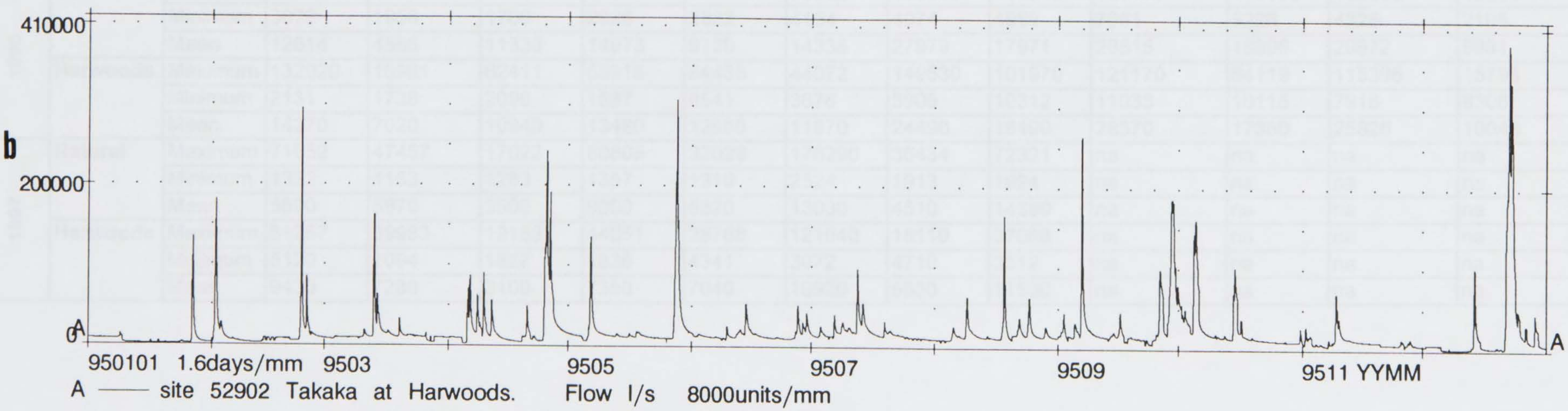
b


260000
200000
100000
0
A
960101 1.6days/mm 9603
9605
9607
9609
9611 YYMM
A —— site 52902 Takaka at Harwoods. Flow l/s 5000units/mm

a


410000
200000
0
A
950101 1.6days/mm 9503
9505
9507
9509
9511 YYMM
A —— site 22222 Natural Flow at Harwoods-Takaka River Item 1 8000units/mm

b


410000
200000
0
A
950101 1.6days/mm 9503
9505
9507
9509
9511 YYMM
A —— site 52902 Takaka at Harwoods. Flow l/s 8000units/mm

	SUMMARY FLOW STATISTICS FOR THE HARWOODS RECORDER: MEASURED AND GENERATED (1995-1997).													
	All figures are in l/s		**January**	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**
1995	**Natural**	Maximum	87259	139970	92917	173470	232510	44044	59794	119180	168750	116270	68249	297280
		Minimum	1158	1562	3075	3564	4413	4972	9892	4979	9983	5178	3696	2179
		Mean	5423	17276	12885	30274	22170	14096	16688	21179	25776	17457	11633	28562
	Harwoods	Maximum	57369	89223	71957	148460	182385	36525	55545	67178	163180	132620	44529	284710
		Minimum	1760	2970	5396	3268	7283	10100	11208	9996	7494	10452	5744	2521
		Mean	5980	14560	13570	24920	22810	15800	19140	19210	30630	25200	11700	26500
1996	**Natural**	Maximum	124650	22243	71160	7883	63483	76986	198690	136540	130470	110550	103300	19904
		Minimum	3072	1958	1706	2928	2882	4154	4074	4989	7081	5226	4325	2105
		Mean	12614	4555	11336	14973	9120	14335	27979	17971	28815	18396	29672	5991
	Harwoods	Maximum	132020	16961	62411	65916	54438	44072	149630	101970	121170	64119	115396	15793
		Minimum	2131	1739	2099	1867	8541	3676	3905	10312	11033	10115	7918	8308
		Mean	14270	7020	10940	13490	12680	11870	24490	18190	28370	17380	25820	10040
1997	**Natural**	Maximum	71052	47457	17022	80805	32029	176290	36434	72321	na	na	na	na
		Minimum	1322	1153	1283	1357	1319	2524	1913	1924	na	na	na	na
		Mean	5690	5970	3500	9000	5820	13030	4510	14390	na	na	na	na
	Harwoods	Maximum	61257	39983	12183	44051	28768	121840	18110	37088	na	na	na	na
		Minimum	5120	1094	1827	1836	4341	3072	4710	3312	na	na	na	na
		Mean	9430	7280	3100	7380	7040	10920	5830	11500	na	na	na	na

LOW FLOW FREQUENCY SUMMARY INFORMATION FOR MEASURED AND NATURAL-GENERATED HARWOODS SITE				
SITE	DAILY MEAN DISCHARGE	FREQUENCY	CUMULATIVE FREQUENCY	% CUMULATIVE FREQUENCY
HARWOODS (Measured)	> 10000	531	531	55
	> 5000	283	814	83
	< 5000	158	972	100
HARWOODS (Natural)	> 10000	381	381	40
	> 5000	220	601	64
	< 5000	335	936	100

Low flow frequency information for Harwoods-generated and Harwoods-natural